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PERSPECTIVE DISPLAYS AND FRAME-OF-REFERENCE: THEIR INTERDEPENDENCE TO REALIZE PERFORMANCE ADVANTAGES OVER PLANAR DISPLAYS IN A TERMINAL AREA NAVIGATION TASK.

BY

TYLER T. PREVETT

B.S., United States Air Force Academy, 1993

THESIS

Submitted in partial fulfillment of the requirements
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PERSPECTIVE DISPLAYS AND FRAME-OF-REFERENCE: THEIR INTERDEPENDENCE TO REALIZE PERFORMANCE ADVANTAGES OVER PLANAR DISPLAYS IN A TERMINAL AREA NAVIGATION TASK.

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Perspective projection and Frame-of-Reference were examined and hypothesized to be dependent on each other in order to realize performance advantages over planar displays. Forty pilots flew simulated instrument approaches on four possible paths to the same runway. Eight subjects were assigned to each of the following display conditions: perspective with egocentric viewpoint location, perspective with a close exocentric viewpoint location, perspective with a middle distance viewpoint location, perspective with a far viewpoint location, or planar array. Results reveal that egocentric perspective displays support better tracking performance than either planar or exocentric perspective displays, while the middle distance exocentric display supported better awareness performance than the planar or egocentric displays. This shows that, indeed, the advantage of perspective displays over planar displays is dependent on the type of performance measure, as well as the viewpoint location. Further, a significant advantage in awareness performance was realized with northbound paths, while tracking performance was not effected by direction of travel. Results are discussed in terms of map display design for electronic approach plates.

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1. INTRODUCTION

The most difficult and perhaps the most dangerous aspect of flight is approaching and completing a safe return to the earth. This danger of approach and landing is apparent from the accident ratio; while compromising only 3% of total flight time, landing and approach account for 47% of total aircraft accidents (O'Hare & Roscoe, 1990). A review of data compiled by NASA via the Aviation Safety Reporting System (ASRS) accomplished by Williams, Tham and Wickens (1992) revealed that geographic disorientation can be a major factor in such mishaps. As a case in point, consider the crash of TWA flt. 514 in 1975, where the aircraft crashed into a mountain near Dulles airport as a result of the crew misinterpreting the vertical terrain features with respect to the approach path and ground features. Due to the potentially lethal prospects of terrain proximal flight, particular attention has been given to the design and implementation of different display formats in order to give pilots a better method of acquiring awareness of surroundings and situations important to their flight. Of course, redesign and implementation of this navigational information is only possible by first examining some of the problems with traditional methods of presenting such information.

Currently, most pilots refer to paper depictions of flight information produced either by Jeppesen Sanderson, Inc., or the United States Government. Figure 1 is an example of such a paper depiction of flight and approach information. This particular instrument approach plate was taken from a Department of Defense booklet to be used by USAF pilots. The paper formats of instrument approach plates (IAP) provided in booklets by either the National Oceanic and Atmospheric Administration (NOAA), or by Jeppesen Sanderson, INC., are used by 90% of US transport pilots (Kuchar & Hansman, 1993a). A useful overview of actual plate usage and content is presented by Mykityshyn & Hansman (1991), and an excellent overview of cognitive issues associated with IAP usage is presented by Clay (1993). These paper approach plates have been criticized for various reasons such as their clutter, inability to support rapid retrieval of information, disruption of pilots ability to read the information, and inability to provide awareness of terrain features (Mykityshyn & Hansman, 1991; Rate &

Wickens, 1993). Rate and Wickens (1993) also state that efforts to improve use of these paper plates have not been satisfactory, necessitating a new approach of plate presentation. The advantages of electronic representation of this information are becoming increasingly salient with new generations of graphic software and hardware, and represent an attractive alternative to the traditional paper renditions. Increased efficiency of updating information, easy access to many different displays, and real time placement of the aircraft within the environment are some of the primary advantages possible with an electronic system of navigational information presentation (Mykityshyn & Hansman, 1991). In fact, some aircraft already use a form of electronic visual representation for navigation, Boeing 757/767 and 747-400 aircraft have an electronic horizontal situation indicator (EHSI) which represents a birds-eye two-dimensional depiction of navigation information and is the primary navigation display in glass-cockpit aircraft (Kuchar and Hansman, 1993a). Thus, the applicability of geographical display equipment is already being realized, but only in a small portion of the aviation community.

For these reasons, several researchers have attempted to compare various aspects of electronic map displays in order to achieve an electronic approach plate which best supports flying tasks. However, electronic display by means of a computer screen also provides many degrees of freedom for the actual display space such as: the amount of terrain to include, the frame of reference to adopt, the dimensionality (2D/3D) to use, or even the number of colors to represent. Hence decisions for graphical design must be made. Given a certain type of display presentation, another question arises; how should pilots performance be assessed? In the next few sections those basic issues of presentation and assessment will be examined in light of research already accomplished. The focus of the present study will then turn to examining inconsistencies between the results of previous studies and manipulation of some of the specified design parameters of electronic display in used for navigation tasks in an attempt to reconcile those inconsistencies.

Assessment Methods

Since examination of design issues will be based on certain measures of pilot performance a brief definition and description of those assessment methods prior to using them as a basis for design parameter specification is appropriate. This section describes two commonly used methods of assessing pilot performance and the importance of those measures.

Local Guidance

In any approach to landing, there is an imaginary ideal flight path which pilots try to follow to the runway. Maintaining an aircraft on this flight path is termed Local Guidance and is considered a form of closed-loop tracking. LG tasks are those that link flight performance and location to a desired performance or loccation, and can be measured by deviations from the flight path. For example, if an aircraft was supposed to be at point (x,y,z) at a given time (t), local guidance assessment is easily seen to be deviation from point (x,y,z) at the given time (t). Alternative ways to compute this deviation are realized by taking either the Root Mean Square (RMS) of that deviation, or the mean absolute value of the deviation. Both of these measures remove the positive or negative sign and leave only an absolute measure.

Another form of local guidance is navigation between two points. In this case, a start point and end point are defined such that the pilot must navigate from one to the other. Interpoint navigation such as this is very similar to way-point navigation, where pilots actually fly from one magnetically defined point to another. Assessing pilot performance using this measure consists of either recording time between points, # of points reached, or deviation from a path between the points by methods stated above.

While defining the construct of LG is relatively easy, abstracting the relative importance of LG error information on different axes is more difficult. How important is 20 feet of lateral deviation, or 20 feet of vertical deviation? It may be argued that vertical errors are naturally more important because there is simply less vertical space as compared to lateral space. Fadden, Braune, and Wiedemann (1991) point out that vertical information needs to be presented on a larger scaling resolution due to the relatively small differences in vertical changes as compared to relative lateral changes in the same time frame, and that vertical instruments must contain some level of prediction to be useful in enhancing pilot awareness, or even for maintaining a specific altitude. The different importance levels of lateral and vertical information are also apparent in the consequences: loss of vertical positioning could result in a crash, while the general consequence for lateral loss of positioning is simply getting lost within the airspace (although the two dimensions will interact in mountainous terrain.) Additionally, the importance of such deviations is dependent on exactly where the aircraft is in its flight. If the desired flight path is 10 feet above the ground at a given time, and the aircraft is 20 feet below the flight path, then the vertical deviation is critical, as it places the aircraft 10 ft below the ground. However, the same vertical deviation at an elevation of 5000 ft is not as important. A lateral deviation of 100 feet while in flight is simply not as important as a lateral deviation of 100 ft when on the ground due to the close proximity of other aircraft, buildings, and runway borders. In general, the closer the aircraft is to the landing, the more important flight path deviations become.

Situation Awareness

With advanced technology aircraat, it is possible for pilots to take off, navigate to their destination, and land without eveer knowing where they are in relation to any terrain features or other aircraft. This does not appear to be a safe or wise way to accomplish a flight mission. For example, what would pilots do if confronted with unexpected severe weather, an intruder into their flight path, or some major mechanical malfunction? Supporting awareness of surroundings is essential to providing the pilot with the information necessary to deal with such unexpected events. This construct is termed Situation awareness (SA), and is used by many researchers to evaluate pilot performance. Andre et al., (1991) propose that the loss of SA can be disastrous, and that higher levels of SA are reflective of safer pilots. SA is a difficult concept to grasp, and even more difficult to actually measure. Pilots, for example, can point out instances or students with excellent SA, but have a more difficult time telling you exactly what SA is or how to objectively measure it (Metalis, 1993). While an exact definition of this construct is not yet fully accepted, over the past decade many researchers have made strides to define what SA is, and how to measure it.

Fracker (1988) compiled a list of different definitions of SA and how SA relates to military flight. One such definition by Tolk & Keether, (1982) defined SA as: "The ability to envision the current and future disposition of both Red and Blue [hostile and friendly] aircraft and surface threats." A definition of SA taken from Whitaker & Klein (1988) indicates that SA is the pilot's knowledge about his surroundings in light of his mission's goals. A more recent definition has been formulated by Crabtree et al., (1993) who suggest that SA: "refers to the pilot's ability to acquire information about the aircraft and the flight environment, process the information and respond appropriately in real time." it is important to note here that SA does not always require the application of knowledge, making this definition somewhat unacceptable.

Endsley (1993a) clearly captures critical features of the above definitions with the following formal definition "the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning and the projection of their status in the near future".

Contained in these different definitions are concepts which make up the general pattern of how to locate and perhaps how to measure aspects of SA. The concepts are the 1. acquisition 2. processing and 3. interpretation of relevant flight information. However, it is important to note that SA may not necessarily involve the application of thatknowledge as proposed by Crabtree et al. (1993). For example, if an approach and landing are completed without incident, then much of the information which the pilot could have used in case of an emergency was, in fact, not used. The specific definition of SA then depends on the relevant flight information, and not necessarily how individuals used that information. If "Red and Blue" or "Enemy and Friendly" aircraft are the most important flight information to the pilot, the most immediately life threatening, then these should be included in the operational definition of SA. Whereas in the realm of commercial terminal navigation areas, the more important flight information would not even involve "enemy or friendly forces" except in terms of how much a mountain or an empty fuel tank could be an "enemy" or a "friend". Thus, the operational definition of SA in this instance would be quite different than the definition of SA to a pilot in a dogfight.

In contrast to the numerous definitions and applications of SA, there is no dispute as to universal importance of SA to the modern day flight environment. In general, all aspects of flight are dependent on the pilot's knowledge of his/her aircraft, and the surrounding conditions. Understandably, pilots with higher levels of understanding about their current situation, and future implications are less apt to undertake a dangerous maneuver, and hence less vulnerable to risk of incident. When pilots find themselves in a novel or dangerous situation, their reactions are greatly dependent on their knowledge of the state of the world. Aside from flight safety considerations, SA is considered an integral part of mission effectiveness. According to Endsley (1993a) SA is "a key ingredient for effective decision making" in dynamic environments such as flight.

Electronic Projection

One key to the support of both LG and global SA is in the choice of appropriate electronic projection techniques. Electronic display technology is rapidly becoming more powerful and taking up less space. A very natural extension of this technology lies in aircraft cockpits. O'Hare and Roscoe (1990) propose that the use of map-type displays for navigation is more desirable than traditional instrument navigation (IAPs) because the displays can show the real-time direct relation between the aircraft and it's surroundings. However, current electronic navigational information systems such as the EHSI in Boeing aircraft usually incorporate only two dimensions of information on the two dimensional display, usually neglecting the graphical, spatial depiction of height which is displayed using only digital numerical readings, or traditional analogue altimeters (McGreevy & Ellis, 1986). Given that display technology is rapidly evolving, this limitation of information representation need not exist. It is possible to create an image or projection on a two-dimensional screen which presents integrated, graphical, three-dimensional information. Such dynamic graphical presentations are already available in almost all home video games and home computers.

Projection of a 3D scene onto a 2D surface is usually accomplished using any of a host of depth cues such as perspective, texture, relative size, height in the visual field, interposition, binocular disparity, or other sources of depth information (See Wickens, Todd and Seidler (1989) for an in depth explanation of these and many other depth cues applicable for electronic display). One of the more complex methods of achieving a realistic 3D interpretation of a 2D screen in a dynamic setting is through the use of perspective. In fact, perspective projection of a 3D scene onto a 2D electronic display represents a paradigm used by many researchers. However, Kim et al. (1987) caution that such a form of presenting three dimensions of information requires careful design of the projection to the display surface. In particular, the method of projection used by the present study and many other studies is called central projection, which produces images similar to those seen by our eyes or through any camera view. This form of display is very similar to simply viewing any scene on a television set where the camera filming the scene is at the actual scene, and the viewer is isolated away from the scene. More formal and precise explanations of perspective geometry are presented by Kim et al. (1987), and Wickens, Todd & Seidler (1989) as well as many other researchers.

In the present study, the projection of the 3D scene is dependent only on the geometric field of view (GFOV) and the viewpoint (location) of the camera in space. In this context, the GFOV is akin to the zoom function of the camera (wide angle to telephoto), and the viewpoint correlates to the location of the camera with respect to some reference point such a runway or an aircraft. As seen in Figure 1.2, an x,y,z coordinates system is defined at the reference point and the location of the camera is specified in terms of a polar coordinates system, where there is an angle away from the polar or x axis (azimuth angle), an angle away from the horizontal xy-plane (elevation angle) and a distance vector from the reference point to the camera.

In different studies, either local guidance performance, SA measures, or both are examined in light of manipulations to these design parameters. The results of some of these studies of GFOV, azimuth, elevation, and distance effects are reviewed here in order to provide a sense of understanding of the implications of varying levels of these variables.

GFOV

The Geometric Field of View (GFOV) is simply the visual angle of the image as seen from the viewpoint or camera. To put it another way, this is the angle of the visual scene at the point where all of the projectors converge on the camera lens. There are two basic effects due to changing the GFOV; distortion and magnification/minification (Ellis et al., 1985). These effects arise whenever the cone of vision adopted by the viewpoint is not the same the cone of vision that would be subtended on your eye if positioned at the same location, creating what is known as a "virtual space effect" (Wickens, Todd, & Seidler, 1989). Figure 1.3 shows a graphical interpretation of magnification/minification effects. Recall the analogy of the camera sending a signal to the television; given that the camera is positioned at the same location, when the GFOV is widened, a greater area is depicted on the television, creating compression of the objects on the screen and hence "minification". Similarly, when the GFOV is narrowed, there is expansion of objects located on the display screen and a "magnification" effect is present. Roscoe (1984) discussed the perceptual complexities associated with such tunneling of the visual field, and indicated that one of the effects of magnification is the removal of depth cues which would be present in wider fields of view, creating the perception that objects are further away than they actually are.

In addition, there is a distorted incongruence of motion in dynamic displays when either of these effects are present, this is due to the viewer assumption that the display view is a "window" and is simply being looked through, as opposed to the reality that the display actually contains more or less of the scene than would be present if looking through such a window (Ellis et al., 1985). Much empirical evidence regarding the implications of these two effects has been gathered by several researchers.

In a study conducted by Kim, Ellis, Tyler, Hannaford & Stark (1987) subjects were required to view a perspective depiction of a target, and track that target with a dual joystick apparatus. Projection parameters were manipulated between trials, and RMS tracking error was recorded. Tracking RMS while viewing from five GFOV angles (8,12,28,48,and 64 degrees) were examined and revealed that tracking error generally increased with increasing FOVs (minification), an effect which can be attributed to decreasing resolution of the display space in terms of graphical pixels per space feet. According to a similar study in 1985 by the same group, GFOV only effects performance substantially when greater than 100 degrees (Ellis et al. 1985)

McGreevy & Ellis (1986) used a static representation of a perspective display and required subjects to judge the elevation and azimuth angles from a reference cube to a target cube while design parameters were varied between trials. GFOV in this case was varied from 30-120 degrees in 30 degree increments. Results indicate that the elevation angle from reference to target was consistently overestimated, this effect was especially pronounced at narrow FOVs. In addition, a GFOV of 60 degrees produced the least overall azimuth judgment errors.

Hendrix, Bjorneseth, & Barfield (1994) examined a task similar to the reference-target cube task used by McGreevy & Ellis (1986). In this particular experiment, GFOV had little effect on azimuth judgments, and smaller GFOVs resulted in small elevation judgment errors.

Barfield, Rosenberg, Han & Furness (1992) also manipulated GFOV in a systematic way. In this experiment subjects were required to fly an aircraft to targets at different locations and altitudes by using an out-of-window display. RMS error was recorded, as well as flight time between targets. GFOV was kept at either 30,60, or 90 degrees for different trials. Consistent with the tracking of Kim et al., Barfield et al. found that the smallest (30 degree) field of view supported lowest RMS error and quickest time reach the next target. In this study tracking performance was best while using narrow fields of view, this result contrasts McGreevy & Ellis' (1986) findings that judgments of azimuth and elevation were best at a wider 60 degree FOV.

The results of the above studies can be summarized and interpreted in the following way: at a given viewing distance from the reference point, smaller GFOV create a greater perceptual resolution of the relative differences between objects. This effect can be attributed to the fact that smaller GFOV results in magnification of the scene, and greater salience of relative differences between objects. Also, it is important to note that these performance results are contingent on the location of the objects, and distortion due to the virtual space effect causes relative perceptual misinterpretations. Simply put; distortions due to the virtual space effect are greater when objects are closer in the actual scene than the reference point or further from the center of the graphical display. It is interesting to note that none of the above experiments reported differences in actual SA as a result of varying GFOV. Performance was assessed in terms of vertical and horizontal judgments, which can be generalized to awareness of relative positioning. One would assume however, that smaller GFOV would lead to worse SA due to greater magnification and a reduced overall view of the scene in question.

Elevation Angle

This parameter is the angle of the viewpoint to the reference point relative to the horizontal plane. An important feature of the elevation angle is that when the elevation angle reached 90 degrees (a planar or birds-eye view) there is no graphical vertical information represented on the display (complete graphical compression of the vertical axis). In this type of planar display, there is only information about relative horizontal distance from the reference point to any objects of interest. The display essentially becomes two-dimensional when the elevation angle is 90 degrees, except for any relative size depth cues which might be noticeable to the viewer. By the same logic, when the elevation angle becomes 0 degrees with respect to the reference point there is complete depth compression, and the only salient information contained in the display is in regards to relative vertical distances. In this condition, the display again becomes essentially two-dimensional, except now it resembles a profile display instead of a planar display. Most of the research reviewed in the GFOV section involved manipulation of the elevation angle as well, and the results of these manipulations are much less ambiguous.

Ellis et al. (1985) used elevation angles from 0 to 90 degrees, in 15 degree increments. The best three dimensional tracking was obtained at an elevation angle of 45 degrees, with performance gradually dropping off to greater values at 0 and 90 degrees. The poor performance at 0 and 90 degrees was attributed to the dimensional compression. Consistent with that explanation, at both extreme elevation angles the gain in performance on the axis orthogonal to the viewing axis was not offset by the loss in performance on the axis parallel to the viewing axis.

The results found by Ellis et al. (1985) were duplicated almost exactly by Kim et al. (1987), who used the same tracking task. Incidentally, little variance was found between elevation angles varying from 30 to 60 degrees, though the best three-dimensional tracking performance was found at 45 degree elevation angles.

In the tracking task studied by Barfield et al. (1992) only used two levels of elevation angle; 30 and 60 degrees. They found that the using a 60 degree elevation angle led to better performance than using a 30 degree elevation angle. This result was evident for both RMS error and in the time to fly between targets. Also, this effect was mediated by GFOV, such that, the advantage for the 60 degree elevation angle in both tracking and time between targets was maintained at smaller GFOV, but disappeared for a GFOV of 90 degrees.

Yeh & Silverstein (1992) conducted an extensive study which involved manipulations of projection parameters as well as different depth cues. In their study, subjects were required to make spatial judgments of relative depth and altitude differences between a reference object and a target object. Viewing orientations [elevation angles] of 15,45, and 90 degrees were used by subjects to make the spatial judgments. Findings included an interaction of viewing orientation and type of judgment. Depth judgments were slightly faster at the 45 degree than the 15 degree, but altitude judgments were much slower at the 45 degree viewing orientation compared to the 15 degree orientation.

Hendrix et al. (1994) partially duplicated the other research endeavors, examining angle judgments between a target and reference cube at depicted elevation angles of -15, 15, 45, 75, and 90 degrees. They found that both elevation and azimuth judgments from the reference point to a cube of interest were best at elevation angles between 15 and 45 degrees. Hendrix and his colleagues assert that the advantage for these lower elevation angles is most pronounced at small GFOVs, when the scene is magnified.

Integration of the above studies yields a straightforward interpretation; both tracking and position judgments using perspective displays are best supported by elevation angles around 45 degrees, and this advantage may be somewhat dependent on maintaining small GFOVs.

One important aspect of these studies with respect to the tracking measures is that most used an absolute deviation from the flight path, and did not separate the different vertical, horizontal or longitudinal errors. Barfield et al. (1992) did take measures of both horizontal and vertical errors, but only reported results in terms of an average RMS error from the flight path. The advantage of the 45 degree elevation angle can be seen as a curvilinear compromise between these different kinds of errors due to the graphical compression of individual axes at different elevation angles. In the one extreme where the elevation angle is 0 degrees, lateral or depth tracking errors will be very large, and will get markedly better with small increases in the elevation angle. By the same token, little information is gained in the depth axis by increasing the elevation angle if it is already greater than 45 degrees. At the other end of the extreme, when the elevation angle is 90 degrees, there is compression of the vertical axis, and vertical tracking errors will be very large. In direct contrast to tracking in the depth dimension, when the elevation angle decreases vertical tracking performance becomes much easier due to a dramatic increase in the amount of vertical information present in the perspective display. Overall error thus reaches its minimum at around 45 degrees. One qualification to this apparent solution concerns the relative importance of accurate tracking in each of the different dimensions. As pointed out by Fadden et al.(1991), vertical tracking is very often more important than lateral tracking and this compromise of 45 degrees might not be the best value for the elevation angle if the relative importance of the different dimensions is taken into account. In the instance that vertical control is more important, the ideal elevation angle would be slightly lower than 45 degrees in order to support more accurate vertical control.

Azimuth Angle

The third of the projection parameters which define the perspective display is the azimuth angle, or the angle away from a straight ahead view. If a horizontal plane were defined by the reference point, with x running foreword-backward and y running side to side, the azimuth angle would be the angle away from a straight x alignment required to intersect the viewpoint location in that xy plane. Similar to the elevation angle, when the azimuth angle approaches a measure which is orthogonal to one of the x or y axes, there is compression of that axis. At the extreme case the axis is completely compressed and relative position information from the reference point cannot be gained in the compressed axis other than through the use of relative size. It is important to note that this azimuth related compression is only apparent with low elevation angles, and that when the elevation angle is great, the compression due to azimuth becomes minimal. For example, at elevation of 0 degrees above the reference point, and 90 degrees azimuth from the polar axis, there is complete compression of lateral (y) axis, but at an elevation angle of 90 degrees (birds-eye view) there is no compression of either the polar or lateral axes.

Ellis et al. (1985) found that for the three dimensional tracking task, the best tracking performance was obtained at 0 degrees of azimuth, where the viewpoint was located directly behind the reference point. Azimuth angle was varied in 45 degree increments, and little decrement in performance was observed between the -45,0,45 degree azimuth angles. Ellis and his colleges also note that tracking performance was poorest at 135 degrees. Apparently, there were two strategies of accommodating different azimuth angles, mental rotation, and a reversal strategy, and at an azimuth angle around 135 degrees, subjects probably experienced confusion regarding which strategy to use.

In their intensive study of perspective design parameters, Kim et al. (1987) varied azimuth in addition to elevation and GFOV. Tracking error due to different azimuth angles mirrored the effects found by Ellis et al. (1985), specifically that RMS error was the smallest when azimuth angles of -45,0, or 45 degrees were present in the display.

In the second of two experiments, Wickens, Liang, Prevett & Olmos (1994) conducted a small scale study in which azimuth angle was fixed at either 0 or 30 degrees. In this particular instance, the reference point was an aircraft which the subjects controlled using a joystick with two axis of control. Airspeed was held constant, and the subjects were to guide the aircraft to a runway landing by way of a flight path displayed in the visual scene. Results showed little performance difference between the zero and 30 degree azimuth angles in terms of either horizontal or vertical RMS error from the flight path, though vertical information was augmented by the incorporation of color coding to depict aircraft height relative to the flight path. In the absence of this color coding it is likely that at the 0 degree azimuth angle vertical tracking would have been quite poor because the vertical predictor symbol was superimposed on the flight path and would have been difficult to perceive. As stated by Fadden et al. (1991), the presence of this predictor symbol in spatial displays is essential for accurate vertical tracking.

It would appear from these three studies that increased error due to increased azimuth is negligible when the azimuth is between -45 and 45 degrees. Error increases at a rapid rate when these boundaries are exceeded, to a maximum at around 135 degrees, and then declines slightly as azimuth reaches 180 degrees, at this angle, the viewpoint is positioned such that viewing the tracking task is along the polar axis, but the lateral control input is exactly opposite of the visual feedback.

Distance Vector

The last projection parameter to be discussed is the distance vector, defined as the length of the vector between the reference point and the viewpoint. Varying this vector in a perspective display is similar to simply varying the scaling of the map. The visual effect is much like the magnification or minification of the scene as presented by the GFOV discussion above, however there are no changes which create variance in the amount of visual distortion. Very often, this variable is manipulated within the context of changes to the GFOV such that the amount of the scene present in the display remains constant. This being the case, differences in tracking error or in SA due to changing the distance vector of the viewpoint are highly dependent on the GFOV.

Ellis et al. (1985) varied the viewing distance from 2.5 to 160 centimeters, and the GFOV was adjusted in order to maintain constant scaling such that close distances had large GFOV, while far distances has smaller GFOV, and the amount of the scene depicted in the display remained constant. There was an increase in tracking error when the distance was extremely small (2.5 cm) and the corresponding GFOV was 119 degrees. The other distances did not show any difference in tracking performance as a function of the position of the viewpoint. It is important to note that the distance effects were mediated by varying the GFOV and that the resulting displays were graphically similar except for the amount of distortion present.

Previously it was stated that Kim et al. (1987) found increased tracking RMS error with increasing GFOV. This result was duplicated for object distance, which was varied independently of GFOV, such that increased object distance led to increased tracking error. This result is in contrast with Ellis et al. (1985) because the distance vector in the former study was varied *independently* of the GFOV, and as the viewpoint was further removed, the resolution of differences between the target and the reference probably decreased markedly.

Yeh & Silverstein (1992) measured spatial judgments for different perspective projection distance vectors such that in one condition subjects had a close viewpoint and in another condition subjects were presented with a more distant viewpoint. Among their interesting results was an apparent interaction between the relative position and viewing orientation. In terms of just the distance vector, they found that the closer viewpoint supported better depth judgments than the far viewpoint, and conversely that the further viewpoint supported better altitude judgments than the close viewpoint.

There is relatively little research in the area of viewing distance, and there is an apparent lack of research as to the effects of this distortion on measures of SA. It appears, however, that increasing distance leads to increased tracking errors, probably due to lack of resolution with respect to the reference point. Also, it appears as though varying the viewing distance from the reference point results in curious effects on judgment in different dimensions, though these effects have only been observed in a small number of studies (i.e. Yeh & Silverstein, 1992)

Summary of Projection Parameters Effects

An overall summary of the effects due to changing projection parameters gives a more solid interpretation and understanding of the implications of perspective projection. It seems that close distances support better tracking (LG), presumably due to increased resolution. This conclusion is reached because comparisons which held resolution constant did not find advantages for these close distances. In fact, Ellis et al. (1985) found that the closest distance led to poorer tracking due to the increased distortion. These same close distances seem to preclude the development of an awareness of the scene, due to the small amount of the visible scene present. In this instance, if the GFOV is widened, minimization occurs and the resolution with respect to the reference point is again reduced. Also, the effects of elevation angle and azimuth angle both seem to be non-linear, with only small costs to tracking up to 45 degrees and larger costs as the angles increase. It is reasonable to propose that these parameters should be set around 45 degrees to get the best performance compromise in tracking axes, and that some intermediate level of distance and GFOV should be set to offset the effects of distortion and resolution in order to maximize both LG and SA tasks.

Therefore, in the present study elevation and azimuth angles are set at 45 degrees, while distance and GFOV are manipulated.

Planar, Profile, and Perspective Displays

As previously stated, planar, profile, and perspective displays are qualitatively different representations of terrain that can be induced by varying projection parameters. The traditional IAP map orientation is a view taken from an elevation angle of 90 degrees. Map depictions of this nature are categorized as a planar display, and have the characteristic that there is no confusion of the two axes presented, though there is complete compression of the vertical axes. A profile display, on the other hand is taken from an azimuth of 90 or -90 degrees, with an elevation angle of 0, which has the property of completely and unambiguously presenting information in the vertical and the forward/backward axes, while creating complete compression along the lateral axes. Perspective displays have some other combination of the perspective parameters which render a simulated three-dimensional surface with some degree of compression and confusion of the different axes. These three specific map depictions have been the focus of comparison for several studies of aviation navigation. The question of which types of displays support better pilot performance is a non-trivial one which bring to light apparent contradictions as to which types of displays should better support either tracking or awareness tasks.

One principle of design which is central to the perspective vs. planar or profile question is the Proximity Compatibility Principle (PCP). Wickens & Carswell (In press) provide an overview of the psychological foundation of this principle, and its relevance to display design. In the aviation domain, the task of flying can be viewed as controlling the aircraft with respect to altitude, lateral deviation, and speed. These three tasks are highly related, and to some extent they depend on each other. For this reason, the PCP stipulates that the integrated tasks of flight path tracking and awareness should be better supported by an integrated (perspective) display, while focused attention tasks such as identifying specific lateral or vertical distances or relative sizes would be better supported by more separated displays (planar or profile) where there is no ambiguity along the judgment axis.

Wickens & Carswell's discussion of this principle describes several specific advantages and disadvantages of using a perspective display in comparison to using planar type displays. *Reduced scanning* is one benefit of integrated perspective display. In a perspective display there is only one image of the aircraft to view, while in an array of 2D displays there are several different and distinct displays, each with their own depiction of the aircraft. Thus, an individual trying to maintain alignment on a flight path while using an array of planar displays would have to scan between the several displays, while an individual using a perspective display would not. The advantage for reduced scanning comes in the form of time savings from the elimination of scanning across several displays.

Another advantage of perspective displays is that they create *display integration.* Images are seen in a more natural or ecological setting, which is closer to what an individual would expect to see if looking on the scene with his or her own eyes. This principle of pictorial realism was proposed by Roscoe as early as 1968. Planar display arrays require individuals to mentally integrate several different displays in order to gain a mental image of the terrain or airspace, while this integration is already complete in perspective displays. The advantage for perspective displays results from the decreased effort to interpret the scene.

However, the presentation of three dimensions of information on two dimensions of display results in the sharing of display dimensions, which in turn creates three disadvantages of a perspective display; poor line of sight resolution, line of sight ambiguity, and axis confusion.

Poor line of sight resolution is the result of distant object compression. In perspective displays, objects are presented as more distant when they are smaller. Much like a set of railroad tracks converging in the distance, perspective displays create a convergence of information at a distance. The differences in depth are conveyed by fewer pixels on the screen than the differences in lateral or vertical position. Planar displays do not have this limitation, as all objects presented in a display maintain their actual scaling, no convergence is present, and resolution of objects in terms of display space is not dependent on that objects location in the actual scene being displayed.

The disadvantage of *line of sight ambiguity* is somewhat related to poor line of sight resolution. This disadvantage results from uncertainty of position along the line of sight adopted by the perspective display. While planar displays also suffer this disadvantage when there is complete visual compression along any one axis, the disadvantage is mediated by the fact that several planar displays may be used in combination. Planar displays overcome this limitation because each provides unambiguous presentation of 2 axes of information, therefore all 3 axes of information can be discerned without compression, though in different displays.

The third disadvantage is *axis confusion*. This disadvantage for perspective displays results due to the fact that each of the three axis has components in each of the 2 dimensions of the display whenever azimuth angle and elevation angle are not 0 or 90 degrees. For example, when there is movement in the vertical dimension of the display screen, that movement can be interpreted as movement in any of the three axes of the x,y,z coordinates system and vice-versa. This same confusion is also evident with horizontal movements in the display screen.

A study conducted by Haskell & Wickens (1993) demonstrated some empirical evidence for the applicability of the PCP to electronic map design, and documented some of the advantages and disadvantages of perspective displays. Subjects were provided either a perspective display or an array of planar/profile type displays in order to pilot an aircraft through a desired flight path. Their findings were consistent with predictions made by the PCP; "for a three-dimensional, spatial, dynamic task, a three-dimensional perspective display is a viable and possibly preferable design alternative to an array of planar instruments." Haskell & Wickens also showed that ambiguity along the line of sight created poorer performance for airspeed control, as the line of sight for the perspective display was directly along the flight path, which was the axis depicting changes in airspeed.

In contrast to the previous study, Andre, Wickens, Moorman & Boschelli (1991) found that the disadvantage of line of sight ambiguity outweighed the advantages of perspective display. In their experiment, subjects were required to navigate to specific locations in a three-dimensional space using either a perspective, or several 2D displays. A greater number of the navigation points were reached using the 2D displays because subjects had difficulty discerning when they had reached the appropriate destination while using the perspective display. Situation awareness was measured in terms of time to recover from disorienting events, and was also better supported by the planar arrays of displays. The advantage of integration was, however, apparent in subjects control inputs, as simultaneous vertical and horizontal inputs were made more often while using the perspective display.

A study conducted by Rate & Wickens (1993) contrasted performance while using a perspective display with a display containing a profile and a planar display. Measurements of performance were taken in terms of lateral and vertical RMS error away from the desired flight path, and situation awareness was assessed in terms of error and response latency to probed questions regarding terrain features. Rate & Wickens found that flight path guidance was better supported by the array of 2D displays rather than the single, integrated perspective display. This apparent contradiction to the predictions made by the PCP resulted from poor resolution of the 3D display, and perhaps some axis confusion.

In a pair of experiments, Wickens, Liang, Prevett & Olmos (1994) extended the work done by Rate & Wickens (1993) in an attempt to identify modifications which would bring perceptive map performance up to the level of 2D map performance. Despite the introduction of several display improvements and additions, Wickens et al. found that planar/profile displays maintained a substantial tracking advantage in the vertical axes, while performance along the lateral axis was not significantly different between the two display formats. In addition, situation awareness was assessed in this study in several ways. Frozen screen tasks were implemented, in which the flight simulation was halted while subjects answered several questions concerning their awareness of the surrounding terrain. Terrain recall was also assessed with a post-flight map reconstruction administered to each subject. The investigators found a slight advantage for perspective maps over the planar/profile combination, including quicker response times but generally greater error rates. These results indicate an absence of exact information in the perspective display, but faster understanding and integration. In terms of the advantages and disadvantages discusses earlier; results from this study failed to find a tracking advantage for the perspective display despite the advantages of reduced scanning and increased integration, while 3D integration led to more rapid understanding of SA tasks.

Ellis, McGreevy & Hitchcock (1987) examined avoidance maneuvers executed by pilots flying with a cockpit display of traffic information. In this case, subjects were required to provide an appropriate maneuver to avoid an air traffic incident given either a perspective display or a planar display. Results indicated that perspective displays supported more vertical avoidance maneuvers, fewer unnecessary maneuvers, and more successful avoidance maneuvers. The success of avoidance maneuvers can be attributed to the fact that subjects had a more realistic and natural depiction of the actual situation, which required no mental integration of information. In addition, Ellis at al. found that the advantage for perspective displays was not evident when there was a head on conflict, which can be attributed to the disadvantage of line of sight resolution or ambiguity along the line of sight. The results of this study were very nearly duplicated by similar studies accomplished by Bemis, Leeds, & Winer (1988) as well as Wise, Garland, & Guide (1993). All of these studies placed the planar displays at a slight disadvantage because they were not implemented with an analog representation of altitude, making altitude change rates relatively difficult to judge.

Kuchar & Hansman (1993b) adopted a slightly different approach to comparing profile, planar, and perspective displays. In the first of two experiments, terrain avoidance maneuvers were examined when subjects were using either a planar, a profile, or a perspective display. In this particular example subjects were given an electronic horizontal situation indicator (EHSI) and an attitude indicator as well as one of the three display types in order to pilot their aircraft. Four terrain hazard levels varying from none to severe were presented to subjects and subsequent avoidance maneuvers were recorded. The authors found less controlled flight into terrain when subjects used the profile display, while subjects were equally likely to impact terrain using the planar or the perspective display. Kuchar and Hansman advocate the use of a plan and profile view to provide unambiguous lateral and vertical information. While this finding demonstrates how ambiguity along the line of sight can lead to undesirable outcomes, there were several aspects of the study which were confounded. Perhaps the most significant of these was the use of only a 0 degree azimuth view for the perspective display. This type of view completely overlays the vertical and longitudinal axes, making judgments in the vertical axis very difficult. The effect is very similar to the effect which may have been seen when Wickens et al. (1994) used a 0 degree azimuth angle, except that Wickens et al. had incorporated color coding of aircraft height information.

The overall summary of the performance differences between the 2D (planar/profile) and 3D (perspective) displays remains quite ambiguous. Neither display type offers a complete advantage in both tracking and situation awareness. In addition, results from these experiments conflict; some found tracking or awareness advantages for perspective displays, while some found tracking or awareness advantages for planar/perspective displays. The questions arise: why the conflicting results? When do advantages associated with perspective displays outweigh the disadvantages; when do 3D (perspective) maps support better performance than 2D (planar-type) maps? One key to answering this question appears to emerge from examining the frame of reference adopted by the perspective display, and this is the issue we consider next.

Frame of Reference

In addition to projection design considerations based on the geometry of the projection, there are also decisions which are dependent on the point of view taken by the display. In the aviation navigation domain, this Frame of Reference (FOR) consideration varies along a continuum from a view where all the presented information is relative to the fixed terrain (a world-referenced frame or 'WRF') to a view where the display is unique to the individual aircraft position and orientation (an ego-referenced frame or 'ERF'). A map presented in a WRF would be useful to all aircraft in the airspace, while a map presented in an ERF would only be useful to the aircraft it is taken from. Navigation and awareness are possible when one can translate ERF information into WRF information, and vice versa. This translation of information has been addressed at length by both Aretz (1991) and Aretz & Wickens (1992). The actual reference frame adopted by a display is a function of these three parameters: the location of the viewpoint, the relative movement of the viewpoint, and the attitude of the viewpoint, Figure 1.5 taken from Wickens et al. (1994), presents these different levels of egocentricity which define the FOR.

Viewpoint Location

Where the viewpoint is located in the three-dimensional space is one of the aspects of frame-of-reference. At one extreme is the pilots eye view, where the viewpoint is located in the aircraft, and depicts exactly what a pilot looking out a windscreen would see. At the other extreme is a viewpoint location very far from the aircraft, looking at the aircraft from a gods-eye view in the context of its surroundings. The pilots eye display is sometimes referred to as an inside-out display, or an egocentric display, while the gods-eye view is sometimes referred to as an outside-in or exocentric display. This frame of reference difference within perspective displays has only been examined by one notable experiment.

Barfield et al. (1992) examined performance differences associated with either an egocentric or an exocentric viewpoint location. They found that the pilots' eye display resulted in shorter distances traveled between targets, and that the advantage for this egocentric display was most pronounced at larger GFOV. Also, target acquisition time was shorter for the pilots' eeye display. Barfield and his colleagues found that the gods-eye (exocentric) display supported more accurate reconstruction of the map. These results were attributed to display compatibility with the mental models pilots had of either the LG or the SA tasks. It is important to note here that the pilots eye display is depicted from an ERF and supported better tracking, while the gods eye display is depicted from a WRF and supported better awareness of the map and terrain.

While manipulation of viewpoint location between conditions has not been the primary focus of many studies, the results of studies which have adopted different viewpoint locations can be compared to examine the extent of an apparent advantage for tracking with an egocentric location and advantage for awareness with an exocentric location as demonstrated by Barfield et al. (1992). Figure 1.4 provides a single, multi-experimental summary of the research relevant to this frame of reference difference. This graph compares performance while using a perspective display to performance while using some form of planar or 2D display, and reveals the presence of an interaction of performance measures resulting from the assumption of different frames of reference. Performance is located on the ordinate, but this measure is intentionally left ambiguous, as each study collected different measures of performance. The abscissa defines the appropriate perspective viewpoint location as either egocentric (pilots eye) or exocentric (some gods-eye view), this dimension is also somewhat ambiguous, as experiments used varying features or dimensions of egocentricity/exocentricity to define their frame of reference. This graphic shows that Haskell & Wickens (1993) compared egocentric perspective view to planar depictions, finding that the perspective supported better tracking than the array of planar instruments. Rate & Wickens (1993), and Andre et al. (1991) compared planar vs. perspective exocentric viewpoint locations, finding that in general, planar arrays supported better tracking performance than perspective displays, while awareness measures indicated an accuracy cost for perspective displays. The studies by Ellis et al. (1987), Bemis et al. (1988) and Wise et al. (1993) propose that perspective displays from exocentric viewpoints support better avoidance maneuvers than planar displays, while Kuchar & Hansman (1993b) showed that this advantage is dependent on the type of incident to be avoided. Synthesis of these results points to the existence of a tradeoff between local guidance and situational awareness. When the viewpoint is egocentrically located, guidance performance is increased and situation awareness decreased. However, when the viewpoint is exocentric, guidance performance increases, while situation awareness may or may not be increased depending on the type of task to be accomplished, and whether that task requires knowledge of the ERF or knowledge of the WRF. In addition, awareness of surroundings with exocentric viewpoint locations is also somewhat dependent on viewpoint motion, which is the second defining factor of the FOR.

Viewpoint Motion

As with viewpoint location, viewpoint motion can adopt either an egocentric orientation or an exocentric orientation. In the case where any one of the projection parameters (azimuth angle, elevation angle, or distance) is linked directly to the aircraft, then that parameter becomes egocentric, and when that parameter is linked to the world axes, it becomes exocentric. Several studies have examined the benefits of making viewpoint motion fixed with respect to either the aircraft or the world, and the results are very similar.

When viewpoint motion is fixed with respect to the world, the actual display does not change with aircraft movements, and when some aspect of viewpoint motion is fixed to the aircraft, then the display changes whenever the aircraft position changes. Comparing the viewpoint fixation on the aircraft to the viewpoint location fixation on world axes is best exemplified by comparing azimuth angle fixation to the aircraft or the world in an electronic display. Fixing azimuth angle to the aircraft creates a track-up type map in which the aircraft remains stationary and the world rotates around. Conversely, when the azimuth angle is fixed to the world, (usually in a North-up fashion) the world remains stationary and the aircraft moves around.

Aretz (1991) examined the design of planar electronic maps. In this experiment subjects were required to navigate an aircraft through terrain, maintaining awareness of surroundings. Aretz proposed that a north-up depiction aids search and identification of landmarks, and facilitates communication with other pilots or air traffic control. Also, the egocentric azimuth (track-up) type maps aided navigational ability and hindered formation of terrain awareness, while the exocentrically fixed azimuth (north-up) map benefited the formation of a cognitive map of the terrain but hindered accurate ERF judgments. Rate & Wickens (1993) also demonstrated a tracking advantage for rotating maps and an awareness advantage for fixed maps. Similarly, Wickens et al. (1994) contrasted egocentric and exocentric features of azimuth with 2D and 3D maps, finding that rotating displays supported better flight path guidance but did not harm awareness.

Overall, it is apparent that when a track-up map is displayed, because azimuth is egocentric there is a relative tracking advantage over a north-up or exocentric azimuth. There may also be an awareness advantage associated with using a north-up map, but this result is not concretely verified in all instances. The relative advantages for each FOR stems from the fact that navigation requires knowledge of both the aircraft and the world. In track-up maps, the ERF is more apparent, therefore ERF tasks such as tracking are well supported. With North-up maps, the FOR adopts a more WRF alignment, better supporting tasks which depend on acquisition of world information such as terrain features.

It is also important to note that a rotating map results from fixing only the azimuth angle to the aircraft, and that other aspects of motion can be fixed to either the aircraft or the world. For example, both the elevation angle and the distance vector can also be fixed to the aircraft, creating a somewhat more egocentric display with respect to viewpoint motion. In a perspective display where all three of the location defining parameters (elevation angle, azimuth angle, and distance vector) are tied to the aircraft, a "tether" view is created and the camera simply follows the aircraft along its flight path from a specific distance and direction away from the aircraft. This is the type of display used in the present study, and viewpoint motion is considered a tether which is egocentric in nature.

Viewpoint Attitude

Another aspect of egocentricity is viewpoint attitude which can be fixed to aircraft or remain stationary. When attitude is fixed to the aircraft, it is considered egocentric, and when attitude is exocentric, the camera remains stable irrespective of aircraft attitude (see Wickens, Haskell, & Harte, 1989). While these relative fixations of viewpoint motion are not a focus of the present study, it is important to understand that there are many aspects of egocentricity/exocentricity which have not been systematically examined. In the present study the camera attitude was exocentrically fixed such that the aircraft attitude was not duplicated by the viewpoint.

Hypotheses

It is suggested from the research reviewed above that the tracking advantage of perspective displays over planar displays is mediated by the FOR adopted for the perspective display, though this effect is not validated in a single, comprehensive experiment. When the perspective display is depicted from an egocentric viewpoint location, the advantages of integration and naturalness facilitate more accurate flight path tracking. At an exocentric viewpoint location, disadvantages of ambiguity, resolution, and axis confusion outweigh the benefits of perspective displays, and tracking performance is worse than when using planar displays. For these reasons, we hypothesize that when comparing perspective to planar displays, tracking will be better with an egocentric perspective display, but worse while using an exocentric perspective display.

Performance on situation awareness tasks appears to be somewhat more ambiguous. There is an advantage for perspective displays that have an exocentric viewpoint location, due to a more natural and integrated view of the world. However, this advantage is applicable only to certain awareness measures that depend on world-referenced knowledge, and not on ego-referenced knowledge. We hypothesize that the best performance on world-referenced awareness measures will come from a perspective exocentric viewpoint location because of logic set fourth by Wickens (1990), Woods (1984) and summarized by Andre et al. (1991): that a 3D view of the airspace provides a more "natural" or "ecological" representation than conventional plan view (2D) displays because a perspective display provides a more compatible view by reducing the need to integrate mentally across several 2D displays.

Given the two hypotheses above, a third hypothesis is manifest if the first two prove correct. This is that there will be a trade off of guidance and awareness. This trade-off will come in the form of increased SA and decreased tracking performance for exocentric viewpoint locations, and relatively lower SA and higher tracking performance for egocentric viewpoint location.

There is little research examining guidance and awareness performance of pilots when the display used is an exocentric viewpoint location and the distance vector is varied. However, given the tradeoff identified above between GFOV and viewing distance, we believe that these parameters could be very important in optimizing the design of exocentric 3D displays. Therefore, a further goal of the present study is to examine the effects of varying this projection parameter when the display viewpoint is exocentric.

Design and Evaluation Considerations

Projection Design

All of the information about planar vs. perspective and egocentric vs. exocentric displays leads directly to the question of design. This section describes some of the major design decisions made in this study for projection design parameters and for aircraft control.

All exocentric locations of display view have not been systematically examined to determine the maximum amount of performance which can be derived from different angles, or even from different distances. For this reason, we made an informed compromise to locate the "camera" for our 3D display at an azimuth angle of -45 or 45 degrees, and an elevation angle of 45 degrees, because these angles were cited as having the greatest advantage for perspective displays. By positioning the viewpoint at this location we avoid significant graphical compression of any of the three axes depicted on the display screen. Also, viewpoint motion was slaved to aircraft motion in order to avoid problems of resolution, and to keep these motion variables of egocentricity constant across all display conditions.

Given a camera location at fixed angles from the aircraft, camera movement slaved to aircraft movement, and a stable camera attitude, we afford ourselves one degree of freedom in exocentric viewpoint locations; the distance from the aircraft. By examining several different distance vectors it is possible to get a clearer picture of the effects of distance on both tracking and awareness. Also, the form of the hypothesized trade-off between Situational Awareness and Local Navigation can be examined in a systematic way by looking at various levels of exocentric viewpoint locations.

Deciding which levels of the factor to test proves to be a bit more complicated than simply dividing the maximum distance into equal portions. For example, if the maximum display distance is 1000 ft away, testing at 0 ft, 250 ft, 500 ft, 750 ft, and 1000 ft would not be completely useful, as perception of displacement and motion is not a linear function of distance. If perception can be related to the visual angle subtended to the eye, than the relationship resembles one provided by Sanders & McCormick, (1987) to define visual acuity.

$$\text{VA (minutes)} = \frac{3438 * H}{D}$$

Or, in trigonometric terms, the equation would be:

$$\text{VA (degrees)} = \tan^{-1} (D/H)$$

Where H is the height of the object and D is the distance from the object. In our experimental situation, a linear change in distance would not result in a linear change in visual acuity. This equation gives us a relation of the VA to distance which is clearly non-linear, but rather of a logarithmic form. For this reason, after assuming a maximum viewing distance of 70,000 display feet, the viewpoint distance was lorithmicaly set at 10,000 ft, 25,000 ft, and 70,000 ft. for each of three exocentric viewpoint locations respectively.

Another display design item which is of importance is control dynamics. In an actual aircraft, entering a roll induces pitch down of aircraft attitude. For this reason, backstick pressure must be added in conjunction with roll in order to maintain level flight. While some studies such as Andre et al. (1991) incorporated this flight dynamic into aircraft control, while other studies such as Rate & Wickens (1993) did not. While this would seem a minor point, by creating two separate dimensions of control, the task of flight guidance essentially became two independent tasks, lateral tracking and vertical tracking. The Proximity Compatibility Principle clearly indicates that advantages are to be gained from integrated display only when the task requires integrated control (Wickens & Carswell, in press). In the present study we have cross coupled the controls in an effort to create an integrated dimensional control task instead of two separate control tasks.

Another area of concern is the level of expertise of participants. Andre et al. (1991) used flight naive subjects, while Rate & Wickens (1993), and Wickens et al., (1994) used pilots with little or no instrument flight time, and Mykityshyn & Hansman (1991) used qualified line pilots. The problem lies in the control strategies adopted by pilots at different levels of expertise. It is *possible* that instrument pilots have different control and observational strategies which impact flight control. Possible strategies vary from merely observing and inputting little control to active and vigorous control and scanning. Research in this area is ongoing, and results are not yet formalized. Since this study involves using electronic IAP charts, the decision was made to use only participants who had some instrument flight training in order to avoid making judgments based on possibly different control strategies of more naive subjects.

Local Guidance Assessment Methods

In the present study deviations from the flight path were considered more desirable than point to point navigation methods due to the nature of the terminal area navigation task. Taking the root mean square (RMS) error at specified time intervals is one computational approach to measuring such deviations, and has been used in several paradigms of research. The actual form of computation involves taking the square root of the average squared deviation from the flight path. While this measure offers an overall average of how far the aircraft was from the flight path without regard to positive or negative deviations, certain limitations are associated with the method. The main problem with the RMS measure is that greater deviations can have disproportionately more weight than closer deviations if computational methods are accomplished in different orders. To rectify this problem, one can either remove the overweighed observations as outliers, or normalize the data by transforming it. An alternative measure of flight path deviation is mean absolute error (MAE), which is simply the average absolute deviation from the flight path. MAE reduces the impact of large flight path deviations without totally removing their presence. In the present study we recorded both to examine post-hoc differences between the measures.

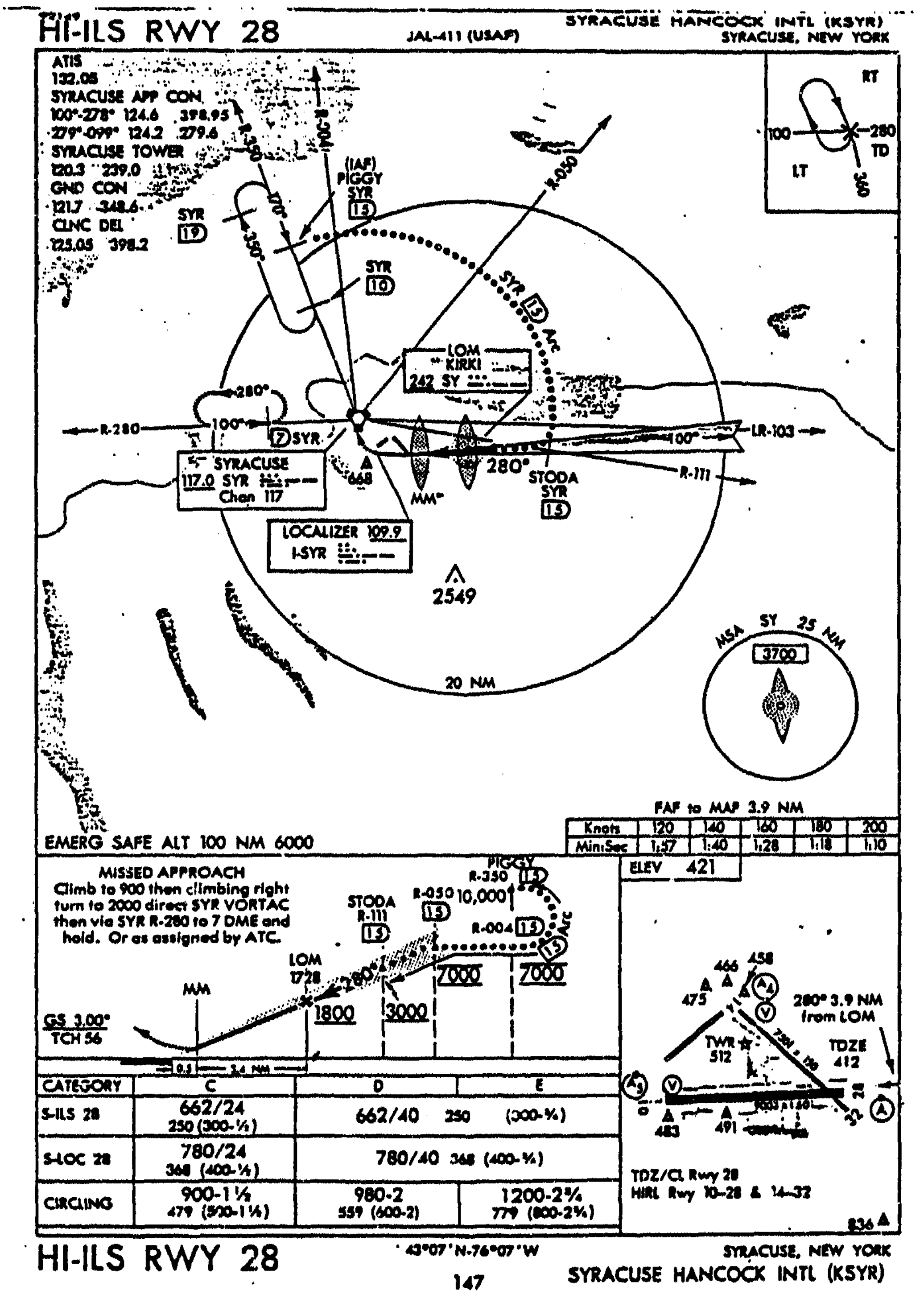
SA Assessment Methods

In the present study, the domain of interest is the terminal area around the runway, and the associated approach to that runway. In the situation where a pilot is approaching a landing there are several items which are of importance. One important item is the flight path. Therefore, knowledge of position away from the flight path is crucial so that the pilot can control the aircraft and maneuver it back to the flight path if it has strayed. Knowledge of landmarks is another important issue in terminal area navigation. Such landmarks include the runway as well as major geographic features of the surrounding terrain. Also, clearances to runway landings are given in terms of "runway numbers" which represent magnetic bearings, and weather information is given in world-referenced terms, so that some knowledge of the world canonical directions is also essential. Fracker (1988) also notes that pilots stay abreast of their immediate situation by operations carried out in working memory, which may incorporate information from both displays and from a long term retention of information. Since the current study will be looking only at terminal area navigation, the operational definition of SA that we use here is: **the availability of flight path information, canonical direction information, and geographic knowledge from both short-term and long term memory.**

Even knowing what SA is does not guarantee usefulness, as it needs to be a measurable quantity in order to compare different levels of achievement. This proves to be a more difficult undertaking than anticipated. Several models of assessment and improvement have been proposed (Endsley, 1993a; Andre et al, 1993; Fracker, 1988; Metalis, 1993) which include knowledge elicitation, verbal prottocol, in-flight report, and post-flight questionnaires.

Knowledge elicitation was used by both Wickens et al. (1994) and Endsley (1993a) as methods of arriving at scores for measures of SA. In both cases, a flying task was temporarily halted in order to ask questions regarding the participants' knowledge of where they were, their flight stage, and other systems. This method will also be used in the current study, and since it can be accomplished directly by the computer, it eliminates any experimenter bias. In addition, all subjects will be asked the same questions at precisely the same time in the flight so that working knowledge of the terrain and flight will be evaluated for each participant in roughly the same situation.

Post-flight questions on terrain, or mission requirements is an approach to be used in the present study as well. Whitaker & Klein, (1988); Wickens et al., (1994), and Aretz (1991) advocate the use of post mission queries. In the latter two studies, participants were asked to reconstruct a map of the terrain. The reconstruction was then evaluated by several individuals to obtain objective metrics of correct positioning, structure, and numbers of objects recalled. Fracker (1988) indicates that this method relies on situational assessments being coded into long-term memory. A similar map reconstruction will take place in the present study.



CATEGORY	C	D	E
S-ILS 28	662/24 250 (300-½)	662/40 250 (300-¾)	
S-LOC 28	780/24 368 (400-½)	780/40 368 (400-¾)	
CIRCLING	900-1½ 479 (500-1½)	980-2 559 (600-2)	1200-2¾ 779 (800-2¾)

Figure 1.1: Paper IAP taken from DOD publication for USAF pilots, depicting IAP similar to those presented by NOAA and Jeppesen Sanderson Inc.

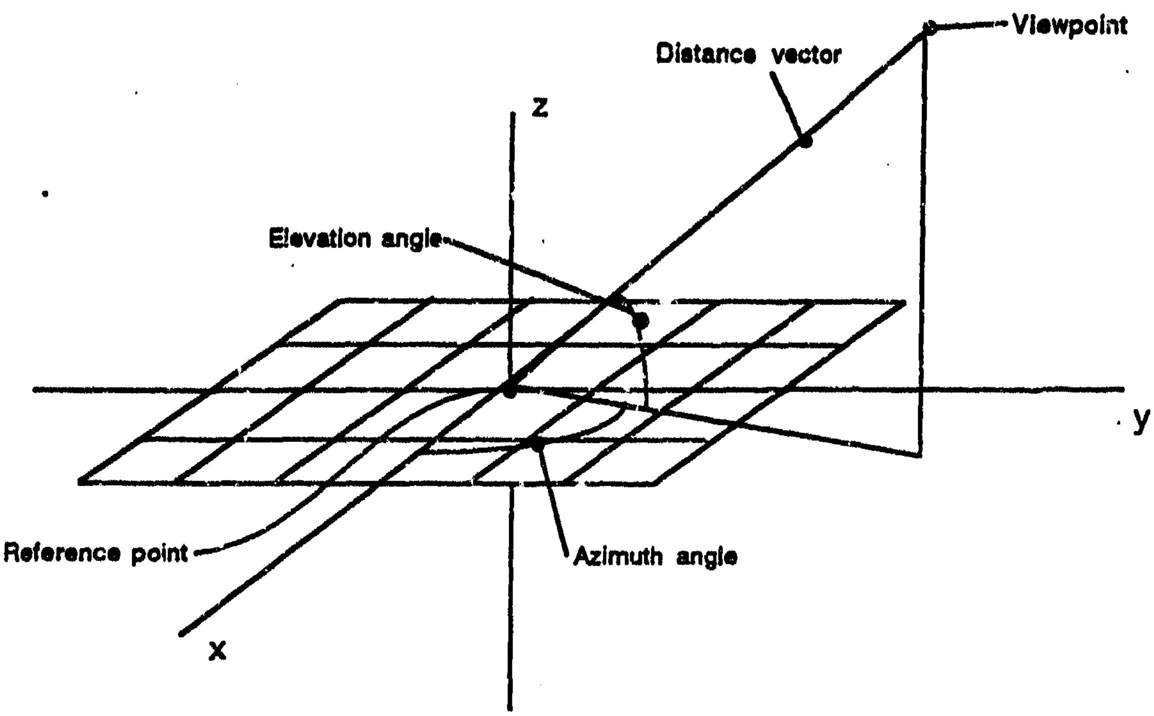


Figure 1.2: Depiction of parameters essential to define a perspective projection.

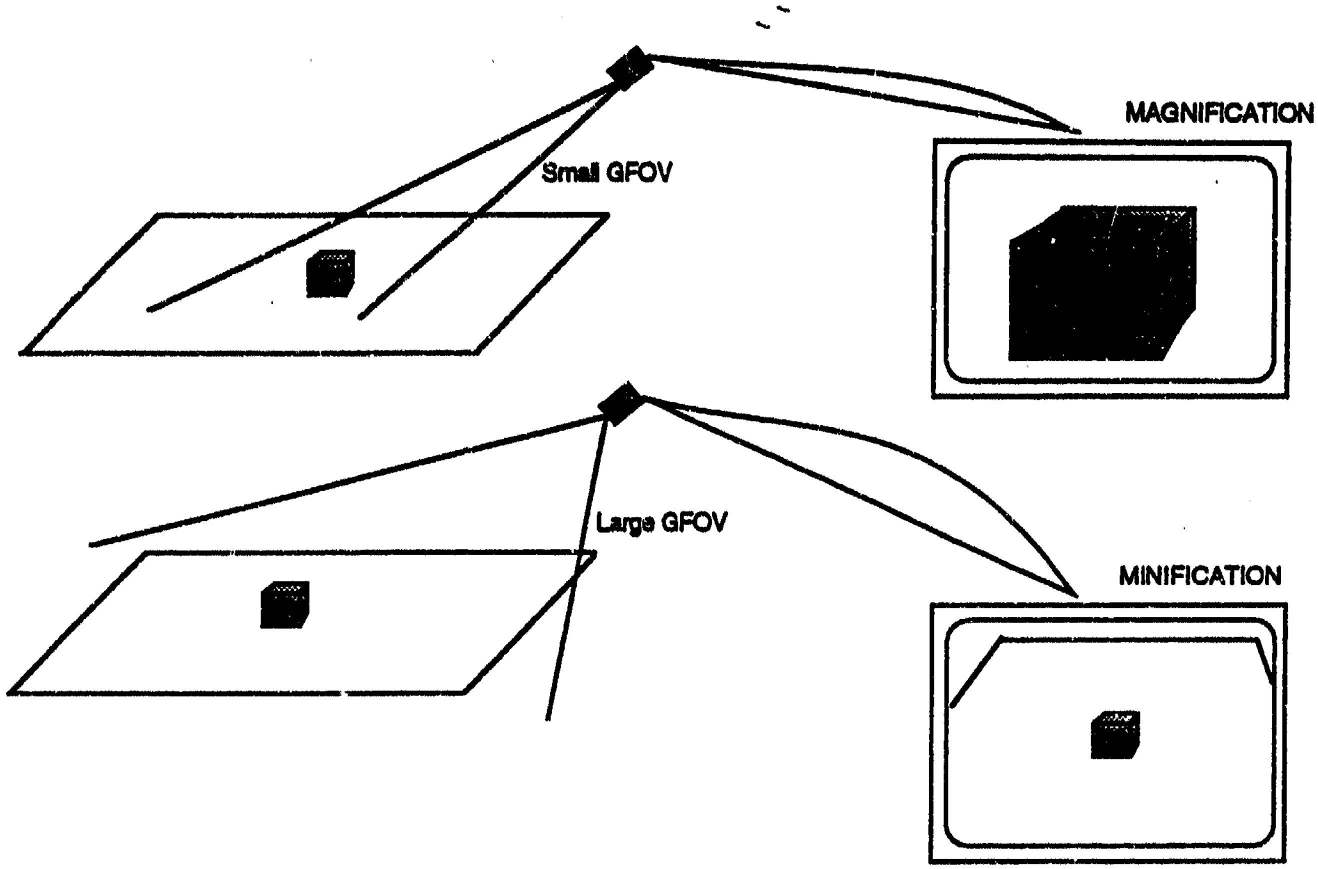


Figure 1.3: Magnification/Minification of the visual scene due different GFOV.

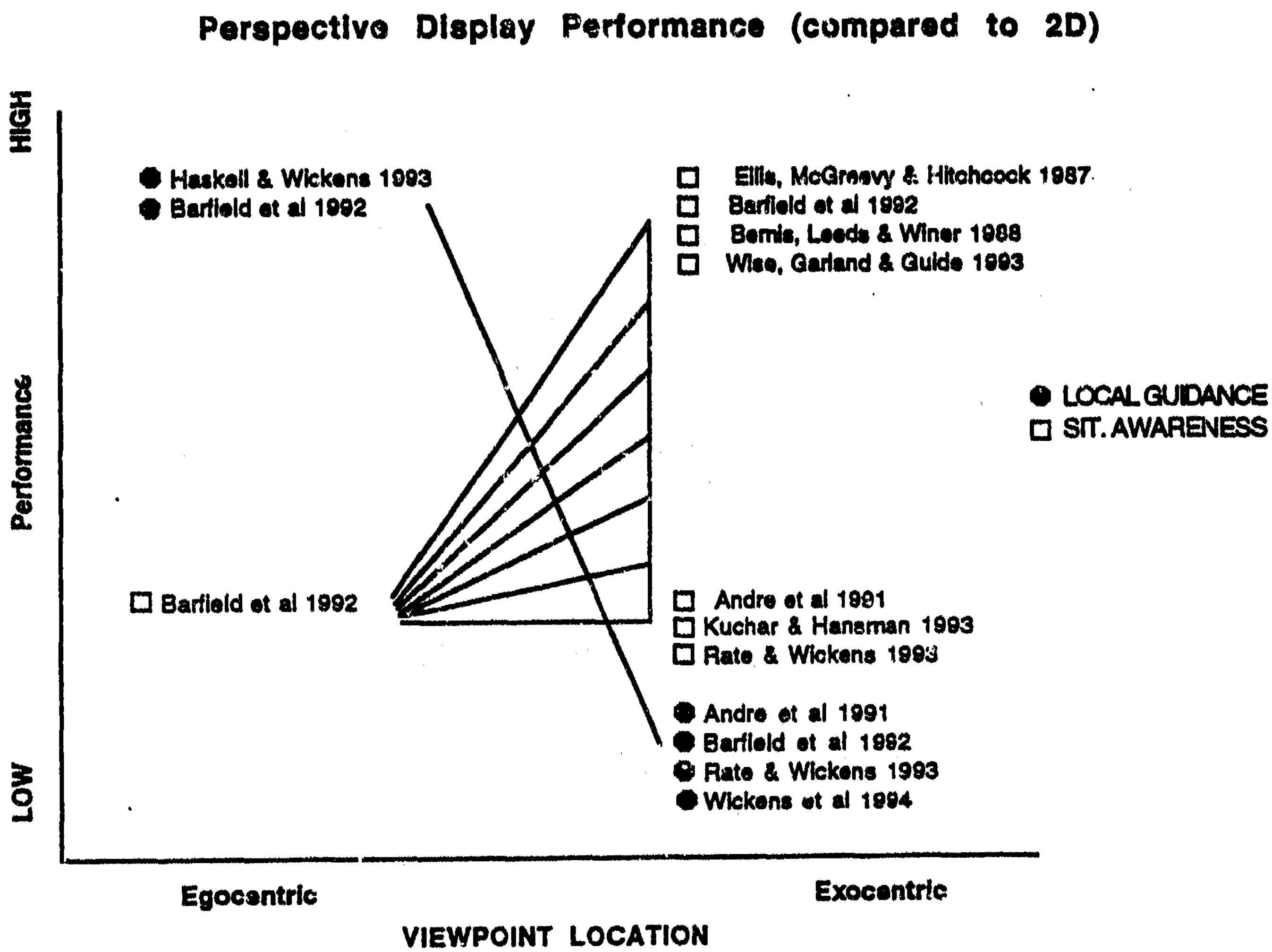


Figure 1.4: Graphical summary of pervious research. All research is in relation to 2D depictions of the same information. Dimensions of the graph are left general in order to accommodate different measurement methods of each paradigm of research. Accordingly, the performance axis is made up of tracking error, time to fly between targets, and various measures of awareness and judgment. The graph points to the existence of a trade off between LG and SA as well as different performance levels using perspective display depending on the Frame of Reference adopted.

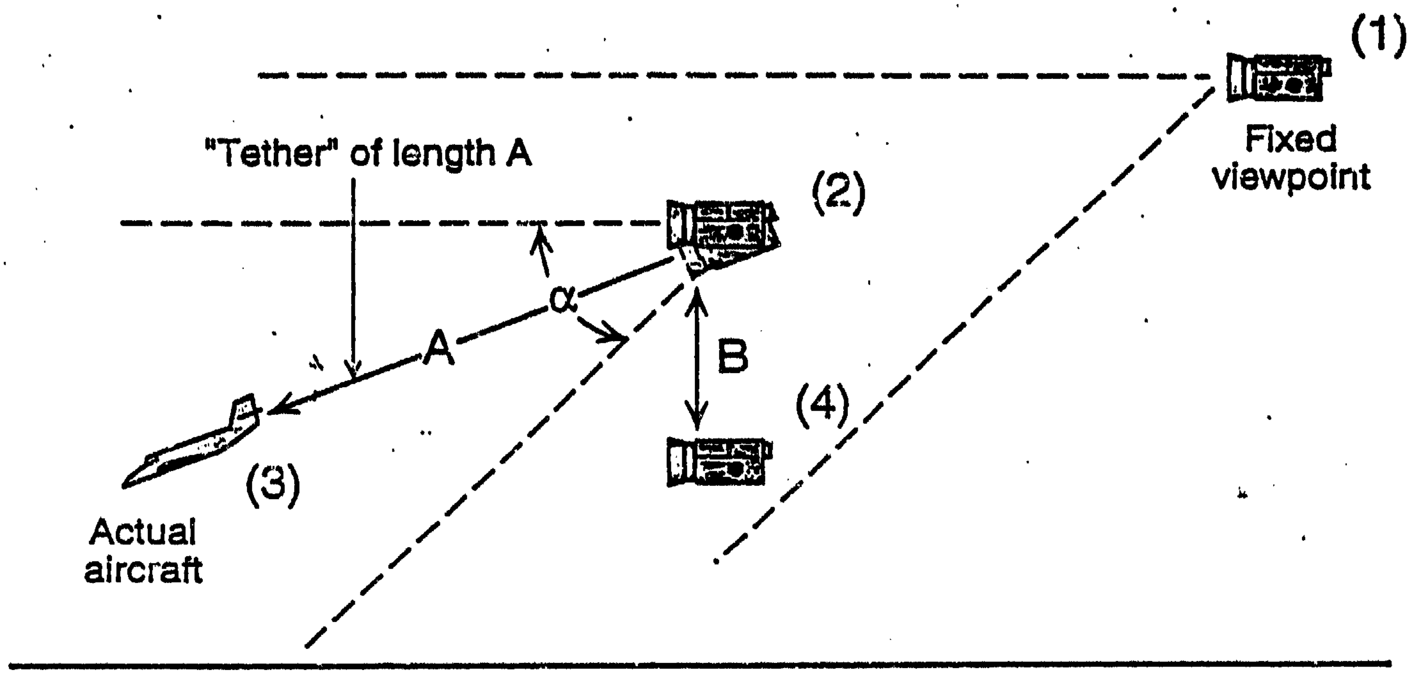


Figure 2: Egocentric features of a 3D display. The display viewpoint can be fixed in earth coordinates (1), or slaved to move with the aircraft as if on a "tether" (2). Once moving, the viewpoint can be positioned at the pilot's viewpoint (like a HUD).(3), or any distance behind (along vector "A"). If behind, it can be positioned at any altitude above the aircraft (along vector B). Furthermore, the viewpoint can have either a fixed elevation and azimuth angle, or angles that are slaved to the aircraft's pitch and roll. The variation in elevation angle (alpha) is shown at position (2). Not depicted in the figure are possible ranges of azimuth angle.

Figure 1.5: Depiction of variables which define the FOR, taken from Wickens et al. (1994).

2. METHODS

Variables

The design consisted of a 4x4x5 blocked design. *Independent* variables include: 1) path type (East or West side of the runway, flying either a North approach or a South approach) 2) Trials (subjects flew four trials each) 3) Display type: planar array, perspective with egocentric viewpoint location, or one of 3 perspective displays with exocentric viewpoint locations. Path and trial varied within subjects, while subjects were blocked into one of the five display conditions.

Four *dependent* variables were measured: 1) Lateral RMS/MAE from the flight path 2) Vertical RMS/MAE from the flight path 3) Short term memory of situation awareness, 4) Long term memory of situation awareness. RMS/MAE, and short term SA were evaluated on each of the four approaches subjects flew, while long term SA was assessed after all approaches had been completed. Both accuracy and response time were measured for short term SA questions.

Subjects

Forty University of Illinois aviation personnel participated in the experiment, each receiving payment of $5.00 per hour and were tested for approximately 1.5 hrs. All subjects were pilots with private licenses and some instrument time, having between 75 and 400 hours of flight experience and ranging from 19 to 26 years of age. Eight subjects were randomly assigned to each of the five map conditions, each flew two practice approaches and all four possible approaches to the runway in counter-balanced order. Subjects received the same instructions (contained in Appendix A), and the same STM and LTM awareness tasks.

Apparatus

The present study was conducted on a Silicon Graphics IRIS workstation with a 16 inch diagonal screen. A two-degree-of-freedom joystick was attached to the right arm of the subjects' chair. This joystick controlled the lateral and vertical axes of the aircraft, with standard aviation control. Pitch was increased with back-stick pressure, and roll was induced with side-stick pressure. Pitch controlled the rate of change of altitude, while lateral stick displacement controlled the rate of roll. The aircraft was not allowed to roll past 90 degrees in either direction. Pitch was cross-coupled with roll such that inducing a roll would result in proportional and simultaneous pitch down of the aircraft. Aircraft speed was held constant at 85 mph, and there were no rudder controls.

Display

Approach path: Figure 2.1 depicts a planar view of the simulated world used for the study in which there were four possible flight paths to a single runway. On a given trial, subjects flew either North or South on the East or West side of the map. Only the East or West side was depicted on the display at a time, and only the flight path being flown was presented to the subject.

Display Conditions: Eight subjects were assigned randomly to one of 5 different display conditions. In each of the displays, the world remained the same, while the variation effected only the view of the world seen by subjects. Viewing distance from the aircraft and FOV were systematically varied and coupled such that the amount of the world in view at any one given time remained the same between the display conditions. Within each display, the viewpoint remained a fixed distance from the aircraft, viewpoint motion was directly linked to aircraft motion, and viewpoint attitude remained fixed with respect to the world such that aircraft attitude did not dictate viewpoint attitude. Keeping viewpoint motion slaved to aircraft motion created a rotating map for all display condition, while fixing viewpoint attitude created a stable viewing platform for the display. The conditions are described in greater detail here:

> *Display 1* was presented from the perspective of the subject sitting in the pilots seat as seen in Figure 2.2. Viewpoint location is considered fully egocentric in this display. Field of view was adjusted such that the amount of the world in view was the same as all other displays, FOV in this case was set at 130 degrees in the horizontal, and 90 degrees in the vertical. Viewpoint attitude was fixed straight in front of the aircraft, while azimuth angle and elevation angle were zero since the viewpoint location was within the aircraft.

Display 2 (Figure 2.3) was presented from the perspective of the subject viewing the aircraft from 10,000 "display feet" from the aircraft. This exocentric viewpoint location requires specification of the viewpoint location. In this and both of the other exocentric perspective displays, both the azimuth angle and the elevation angle were 45 degrees. Azimuth angle was adjusted to either 45 degrees or -45 degrees (the right or left side of the aircraft) so that the simulated world would always be in the background. The distance vector from the viewpoint to the reference point (aircraft) was 10,000 display feet, and the FOV in this case was 120 degrees and 60 degrees horizontal and vertical respectively.

Display 3 (Figure 2.4) was presented from the same view as display 2, with the exception that the viewing distance vector was 25,000 display feet. This exocentric viewpoint location required the manipulation of GFOV in order to maintain a homogenous amount of the world in the display; the FOV was maintained at 80 degrees in the horizontal, and 50 degrees in the vertical.

Display 4 (Figure 2.5) was the same view as 2 and 3 with the exception that the viewing distance was 70,000 ft. FOV was further narrowed to 45 degrees in the horizontal, and 30 degrees in the vertical in order to maintain the quantity of the world visible to subjects.

Display 5 (Figure 2.6) was a 2 dimensional plan view depiction of the world, subjects were presented two displays, one planar view of the world to give lateral information, and one profile depiction to relay height information. Both views had a fixed aircraft and a moving world.

Augmentations: Several artificial augmentations were incorporated into each display to aid the subjects in their flight, and can be seen in Figures 2.2-2.6.

Each cardinal direction was clearly depicted on the world terrain with a white arrow, and labeled appropriately N,S,E, or W.

In addition to the actual flight path, a "margin of error" was also included, which represented 100 ft. of vertical or lateral deviation from the desired flight path. This path was presented in blue, and created a perceptual flight "box" to judge error from the desired flight "path".

The aircraft was color coded to depict vertical deviation from the flight path. Five color levels were used, white to indicate > 70 ft above, gray to indicate between 70 and 35 ft above, black to indicate a deviation of less than 35 ft, yellow for between 35 and 70 ft below, and red to indicate > 70 ft below the flight path.

A directional predictor was added to the display, which served as an extension to the aircraft and created an extra long nose so that subjects could better see where they were heading, both in the vertical and the lateral axes. The end of the nose and the rear of the aircraft were placed on "poles" which connected the aircraft to its shadow on the ground, thereby giving more height information. This type of augmentation was advocated by Ellis et al. (1987).

Finally, an attitude display indicator (ADI) was added at the top center of each display to assist flight control. The ADI was configured such that the aircraft symbol banked within the display, while the pitch indicator bars moved to depict pitch inputs. The aircraft symbol in the ADI was white, while the pitch indicator bars were black.

Performance Measurement: Situation Awareness was assessed as guided by the operational definition arrived at in the introduction. Both long term and short term memory of the situation and world were assessed using multiple choice questions referring to geographic features and flight path orientation.

Short term memory: At a given point on each flight path, the simulation stopped, the screen was blacked out, and subjects were prompted a series of questions to assess their awareness of the situation at that moment. Accuracy and response times were recorded automatically upon depressing a 1,2,3 or 4 on a computer keyboard, and subjects were informed that both response time and accuracy were important as performance measures. Locations along each flight path where the frozen screen tests occurred are depicted on Figure 2.1, while the actual questions asked are located in Table 2.1. All eight questions were asked at each frozen screen location. The questions asked of subjects were derived from a survey administered to eight instructor qualified pilots from the University of Illinois, the actual questionnaire is contained in Table 2.2. Overall, instructors indicated that they assessed SA in several different ways, including but not limited to: knowledge of the runway location, knowledge of future flight requirements, and knowledge of general location in relation to world objects and to a desired location. The questions in Table m-1 are designed along these specifications. Note that half of the questions are specifically designed to assess the subjects' knowledge in an ego-referenced frame (the odd questions) while half of the questions are designed to assess knowledge in a world-referenced frame (the even questions).

Long term memory: After completing the two practice flights and the four trial flights, subjects were given a post-test to ascertain how much of the world they had committed to a longer term memory store, as SA depends on both information available temporarily, and information pulled out of a longer lasting store (Figure 2.7). Subjects were given a sheet of paper which contained only the runway and the cardinal directions. They were then given paper cutouts of the objects in the world and were asked to place them on the paper as they had appeared in the world. Subjects were evaluated on the correctness of their positioning of the terrain features.

Tracking: performance was recorded using RMS error and MAE from the flight path in terms of lateral deviation and vertical deviation. Error was sampled at two cycles per second and averaged over 3 portions of the flight path corresponding roughly to the downwind, base, and final components of the flight path.

Procedure

Upon arrival, subjects were given a demographic questionnaire in order to record age and flight experience. Subjects were then given instructions on what tasks would be required of them during the experiment (Appendix A). All participants were informed that their participation was entirely voluntary, and though their participation was greatly valued they could decline to complete the experiment without forfeiture of pay earned up to that time. No subjects declined to complete the experiment. After reading the instructions and being informed of the nature of the experiment, subjects were seated in a dimly lit and isolated room where the apparatus described above was located.

Subjects completed two practice trials under close supervision of the administrator, and were provided opportunity to ask any questions about their particular display. The administrator made sure that all subjects understood the symbology and the display by the conclusion of practice rounds. A door was then closed and subjects were provided with an undisturbed and isolated environment in which to perform the experiment. Recorded trials were initiated by subjects in order to provide rest periods between each trial.

After completion of all trials, subjects were given a post-test designed to test long term memory of the terrain, as depicted in Figure 2.7. A subjective evaluation was then administered to subjects in order to compile relative perceived difficulty of each of the display types. As Table 2.3 shows, relative difficulty was rated on a scale of 1-10, 10 being very hard, while actual questions were aimed at different aspects of the flight as experienced using the particular display type assigned.

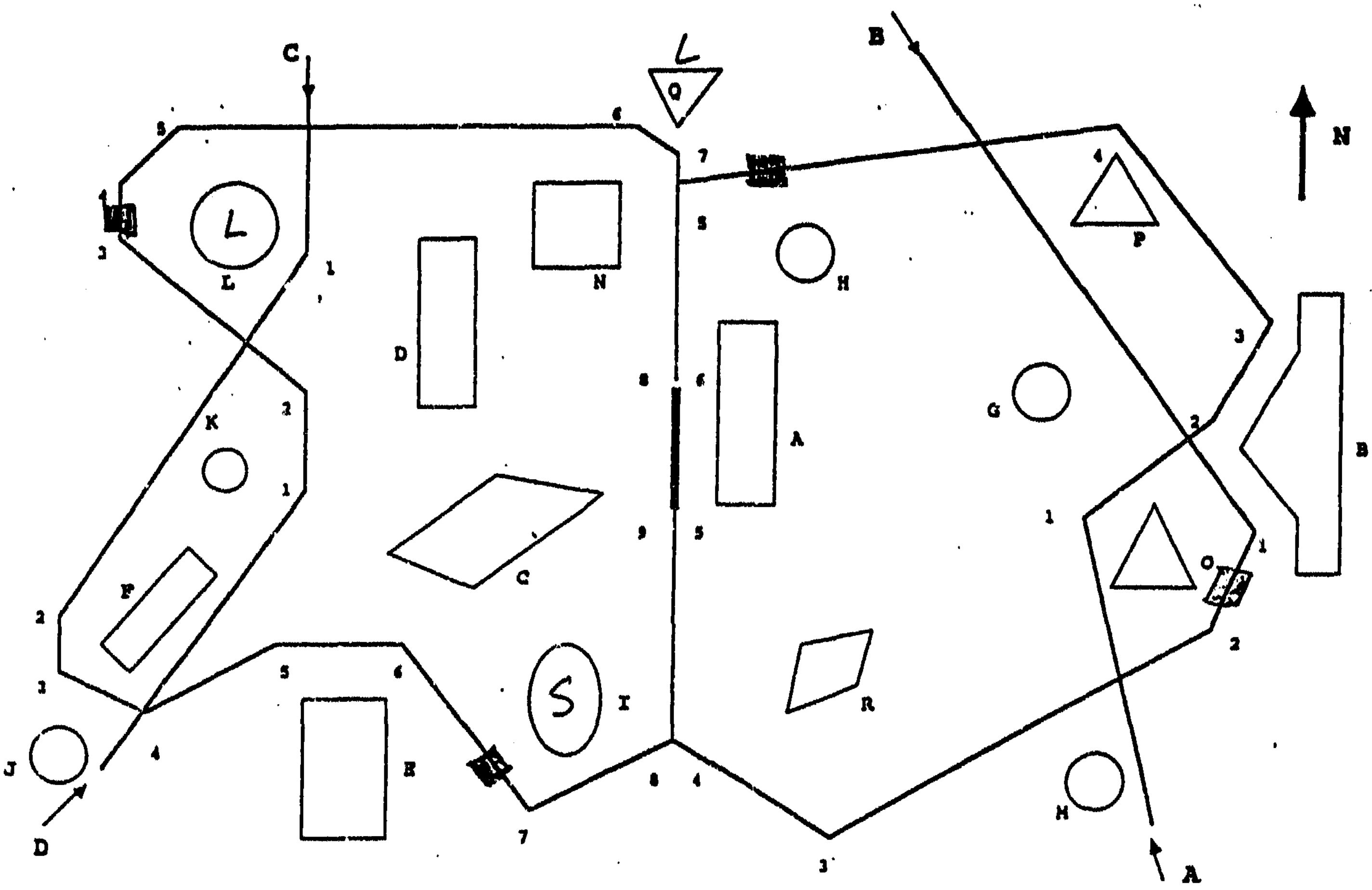


Figure 2.1: Layout of the simulated world through which subjects had to fly. Line indicate flight paths, boxes indicate locations of frozen screen tasks.

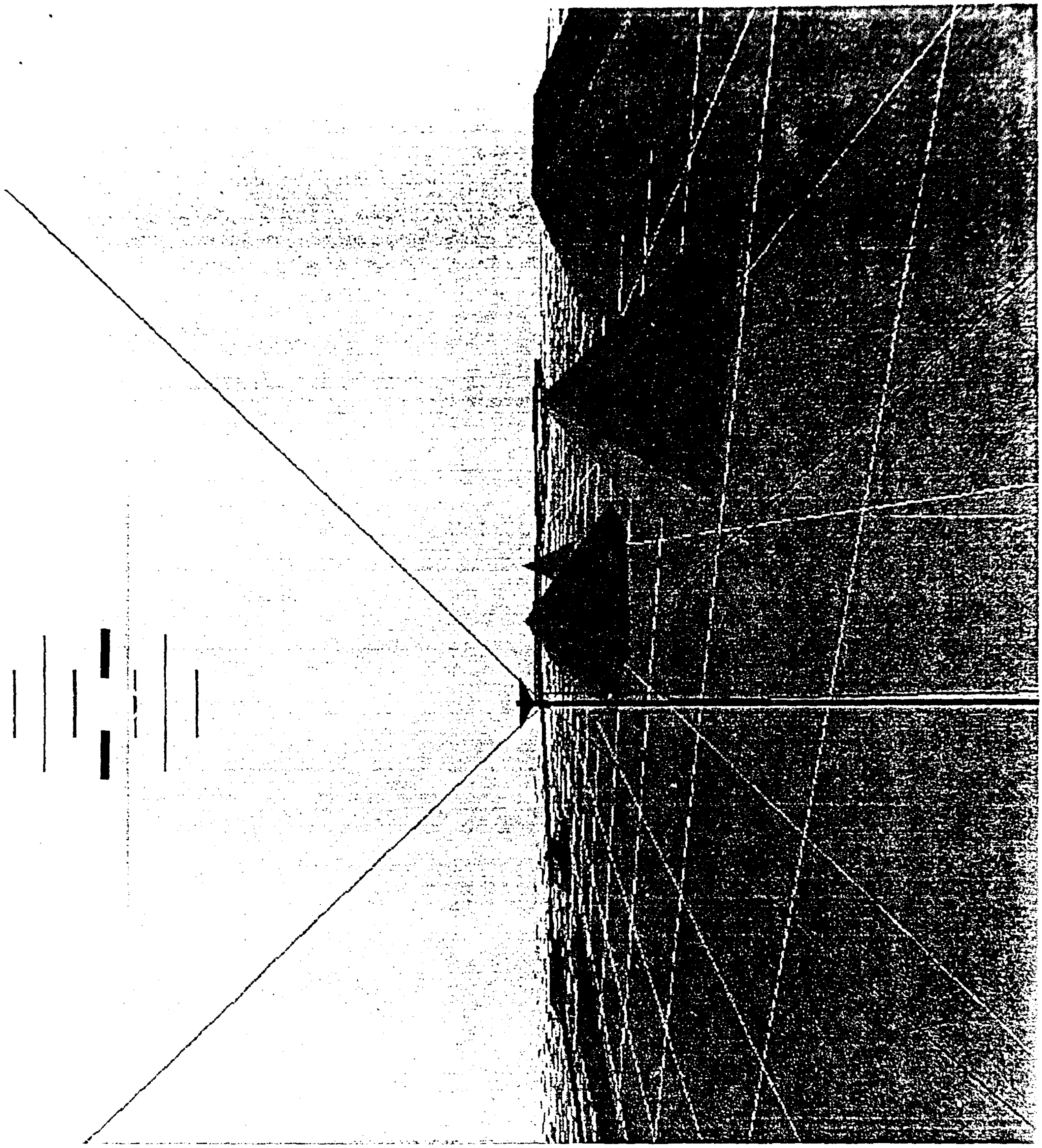


Figure 2.2: Perspective display with an egocentric viewpoint location.

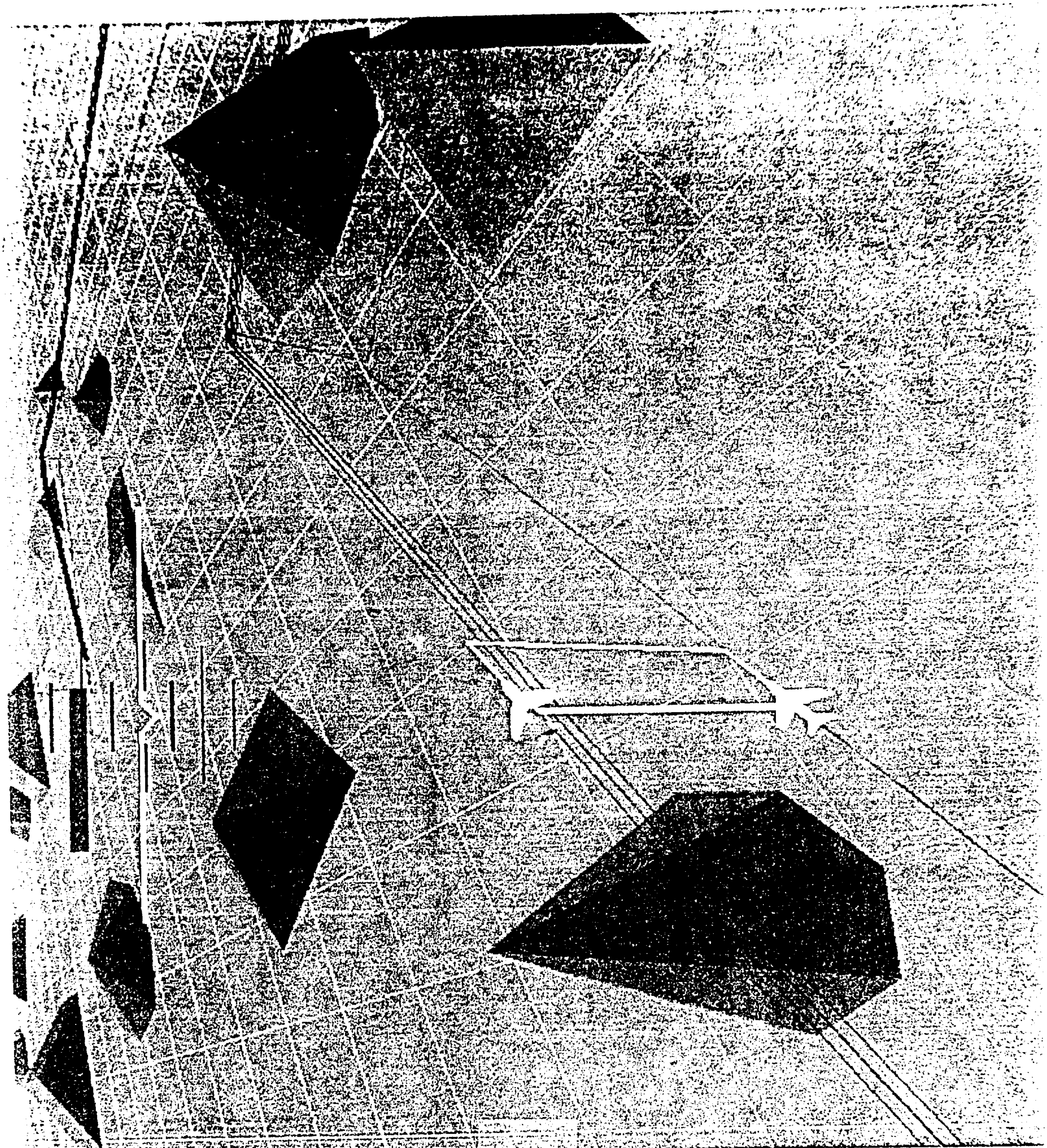


Figure 2.3: Perspective display from an exocentric viewpoint location 10,000 ft. away from the aircraft.

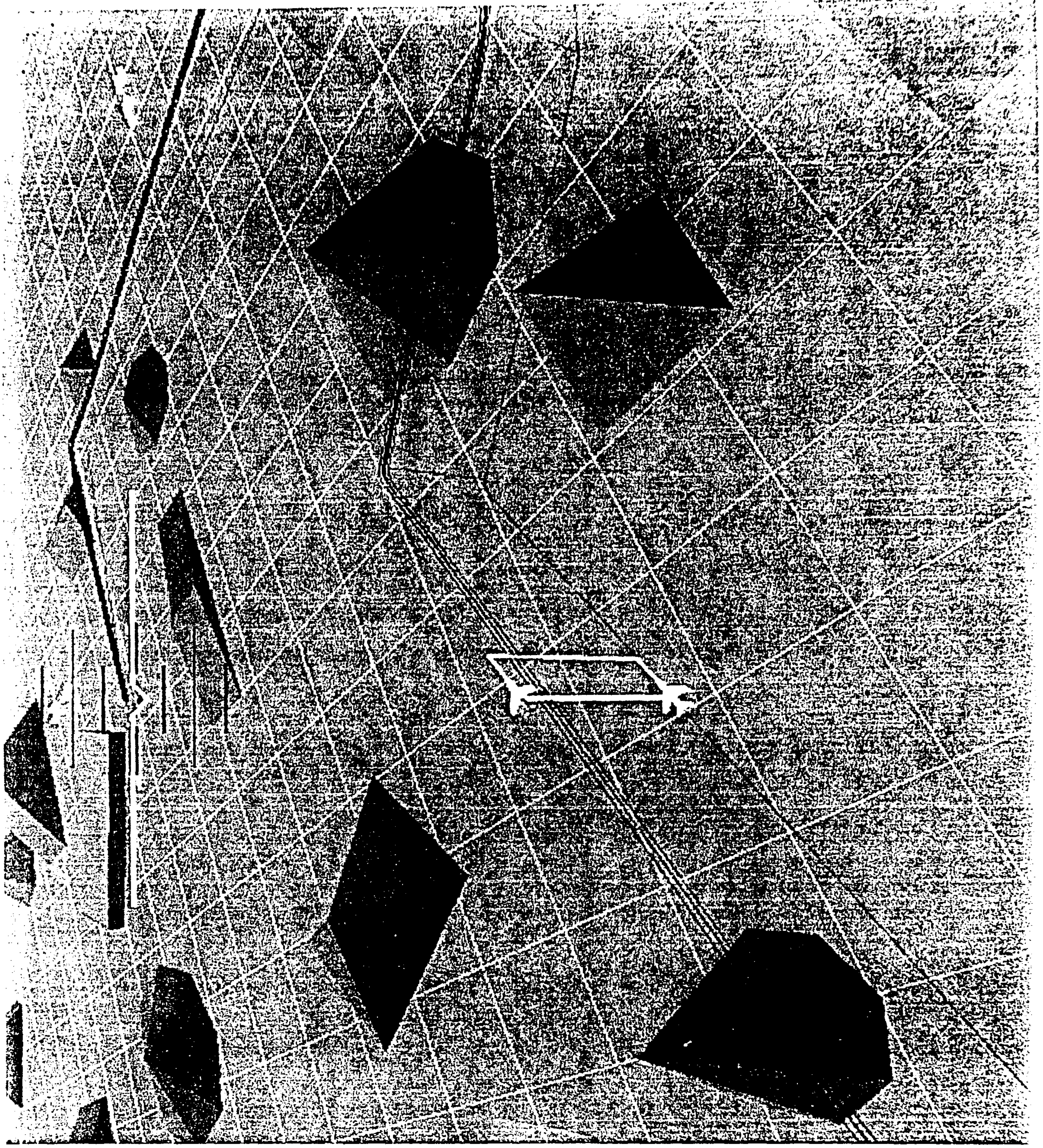


Figure 2.4: Perspective display from an exocentric viewpoint location 25,000 ft. from the aircraft.

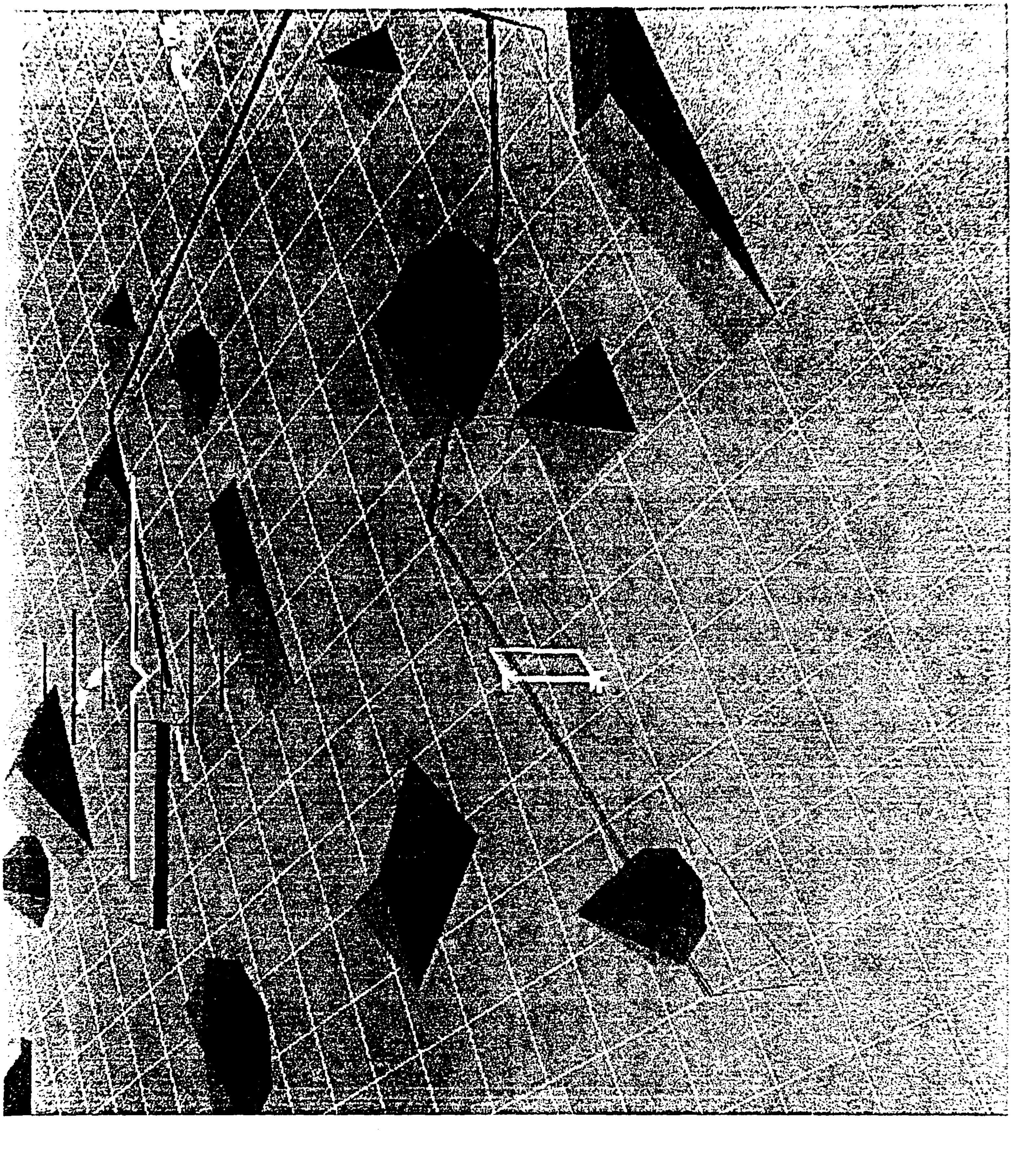


Figure 2.5: Perspective display with an exocentric viewpoint location 70,000 ft. from the aircraft.

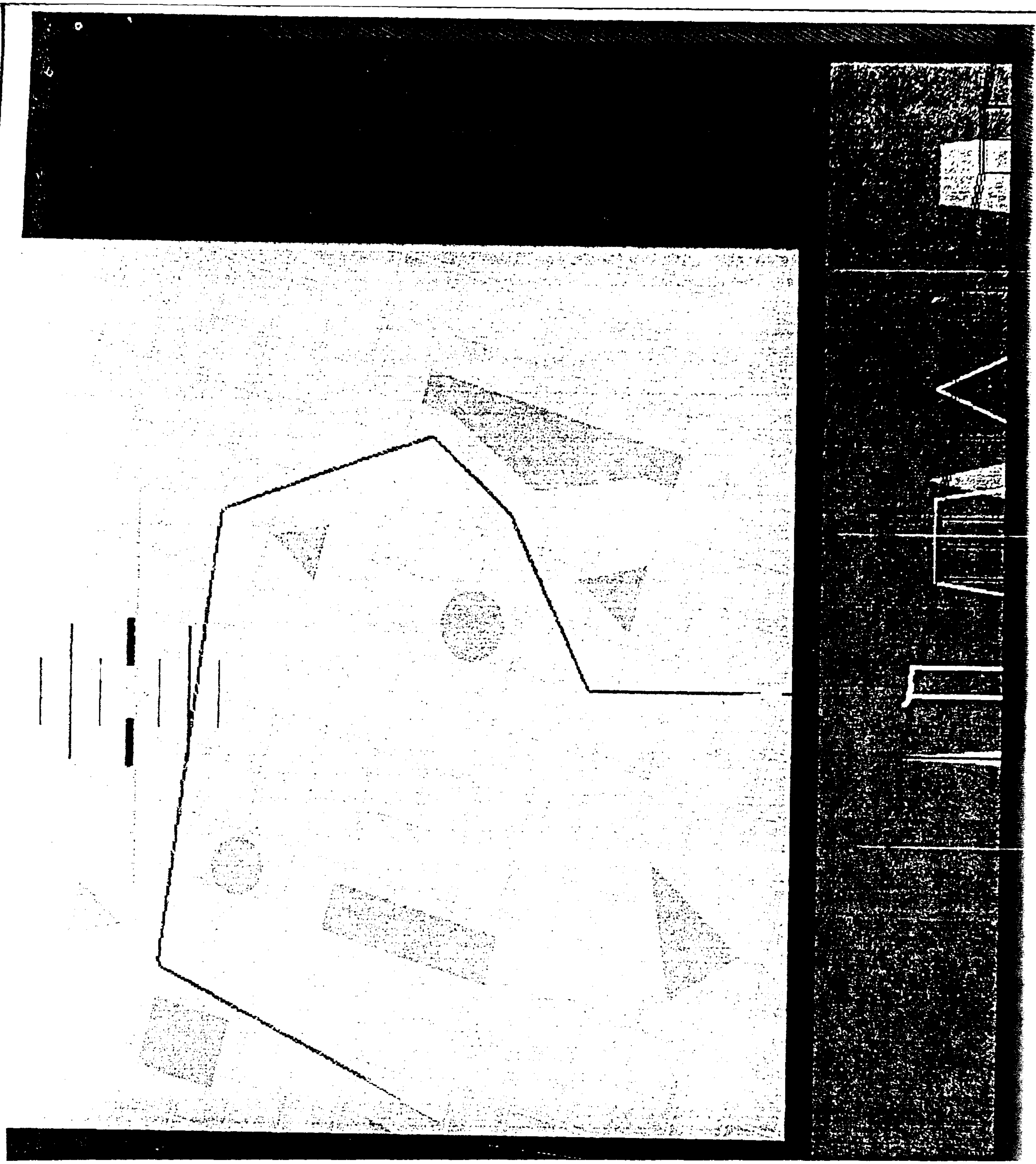


Figure 2.6: Planar display

INSTRUCTIONS: **Subject# ______**

1. **Draw the objects at the lower left where they appeared in the experimental world. Use each object only once.**
2. **Label each object as "H" higher than the flight path or "L" lower than the flight path.**

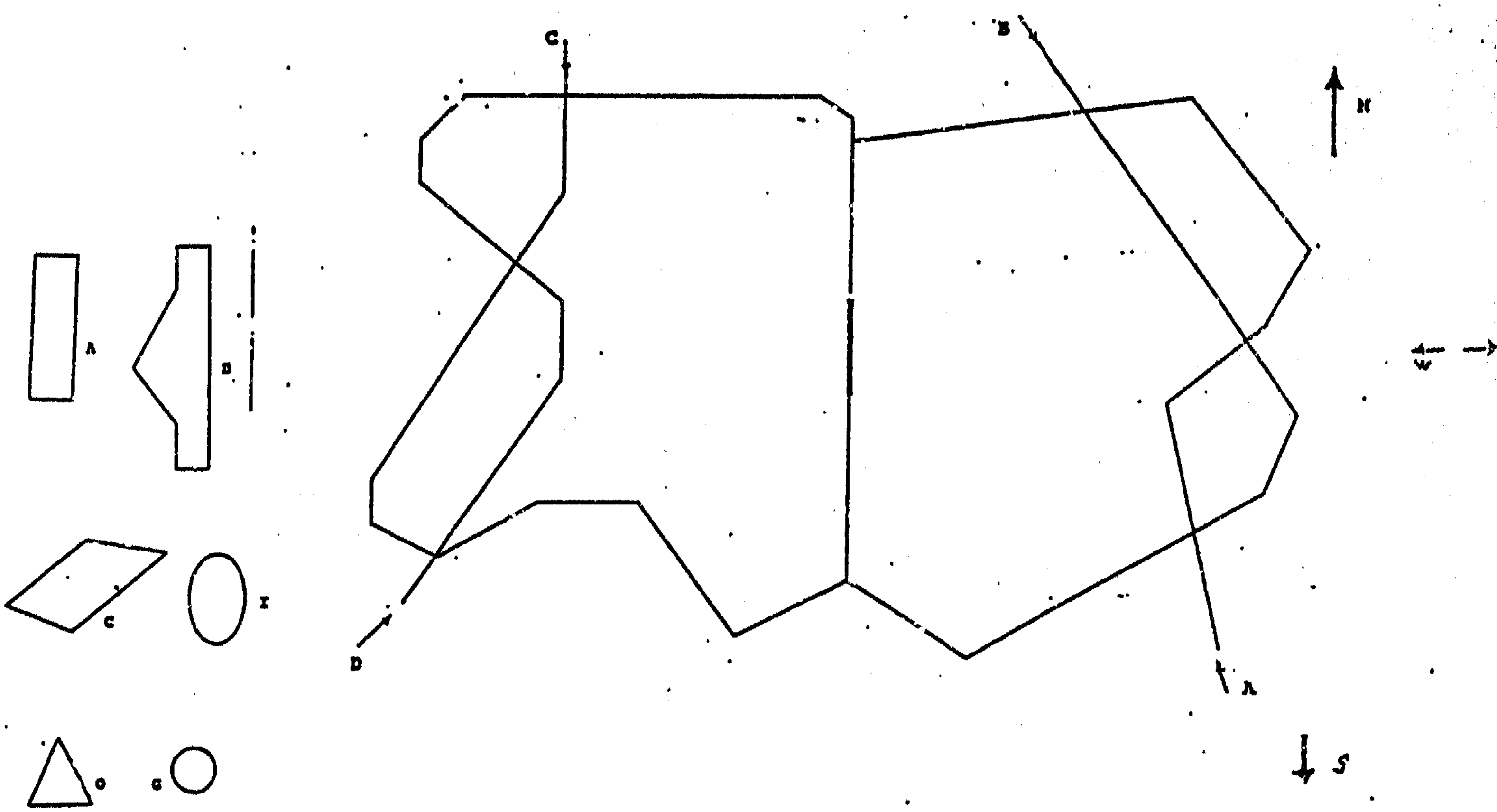


Figure 2.7: LTM map reconstruction task

1. [ERF] Where is the runway to you?
    1. right, front
    2. left, front
    3. right, behind (or even)
    4. left, behind (or even)

2. [WRF] In which general direction is the aircraft traveling?
    1. North
    2. South
    3. East
    4. West

3. [ERF] What was the next turn on the flight path like?
    1. right, > = 45 degrees
    2. right, < 45 degrees
    3. left, > = 45 degrees
    4. left, < 45 degrees

4. [WRF] Generally, where is the runway from the aircraft?
    1. North
    2. South
    3. East
    4. West

5. [ERF] What is your Aircraft's position relative to the flight path?
    1. above and to the right of the flight path
    2. above and to the left of the flight path
    3. below and to the right
    4. below and to the left

6. [WRF] In which direction will the next turn take you?
    1. more North
    2. more South
    3. more East
    4. more West

7. [ERF] Is the peak of the terrain feature located to your [right, left] higher or lower than the flight path?
    1. peak is higher
    2. peak is lower
    3. same height
    4. don't know

8. [WRF] Is the peak of the terrain feature located to the [N,S,E, or W] higher or lower than the flight path?
    1. peak is higher
    2. peak is lower
    3. same height
    4. don't know

Table 2.1: Short Term Memory SA Questions (during flight) odd questions are from an Ego-reference frame, while even questions are from a World-reference frame. ERF and WRF notations were not present for actual experimental presentation.

Dear Instructor,

A current project being conducted at Aviation Research Laboratory involves the study of electronic approach displays as a means to replace the use of conventional paper plates such as Jeppesen charts. One important aspect being examined in this study is the concept of situation awareness. In other words, how well do the displays give local(the aircraft is above and to my right) and global(the thunderstorm is west not left of the airport) information. The item to examine is easy to determine, what is not so easy is how to measure a concept such as situation awareness. This is where your experience is highly needed, please take a few moments to answer the following question.

What are some typical questions that you would ask your students in order to determine their level of situation awareness? This includes in the aircraft and on the ground.

Your input is greatly appreciated. Thank you.

Table 2.2: Instructor Questionnaire administered to eight University of Illinois Institute of Aviation instructor pilots.

SUBJECT #_______

Using the following scale, please answer the following questions.

Very easy		Mod. Easy		not very hard		kinda hard			Very Hard
1	2	3	4	5	6	7	8	9	10

1. Controlling the aircraft's attitude _______

2. Getting information off of the terrain to answer questions _______

4. Recalling if terrain features were "to the right, left" _______

5. Answering questions such as "to the North or South" _______

6. Remembering what the terrain looked like _______

7. Estimating proper control inputs to stay on the flight path _______

8. Height judgments _______

9. Lateral judgments _______

10. Overall difficulty of the flying experience with your type of map. _______

Table 2.3: Subjective Evaluation forms used to evaluate perceived difficulty of different aspects of flight given one of the display conditions.

3. RESULTS

Tracking Performance

Examination of deviation data in terms of RMS and MAE showed that MAE data had fewer outliers and was less skewed, therefore, MAE was used to evaluate tracking performance. Horizontal and vertical tracking were effected only by the display type. There were no trial or path effects, and nno interaction between any of the independent variables.

Horizontal: Deviation error in terms of horizontal MAE is presented in Figure 3.1. A repeated measures ANOVA with subjects nested in display type was carried out, and revealed a significant main effect for map type $F(4,120) = 106$ $p<.0001$. In addition, a Tukey analysis for all pairwise comparisons (TMC 120df, $P<.1$ for family of comparisons, $P<.01$ for each comparison) revealed that the egocentric view supported better performance than the rest of the maps, while the far-exocentric view supported poorer performance than any of the other map types. There was no significant difference between the close exocentric, the mid exocentric, or the planar condition.

Vertical: A similar analysis was performed on the vertical error data, plotted in Figure 3.2. There was a significant main effect for map type $F(4,120) = 62.7$ $p<.0001$. Tukey multiple pairwise comparisons analysis demonstrated that the egocentric view and the planar view supported better vertical performance than the other display types, while the close exocentric view provided the worst performance of all display types (120 df $P<.1$ for the family of comparisons $P<.01$ for each comparison). There was no significant difference for vertical tracking between far and the mid exocentric view, nor between the planar and egocentric views.

3D Exocentric Isolation: Figure 3.3 represents an isolated depiction of the influence of perspective displays with exocentric viewpoint locations on both horizontal and vertical error. This figure clearly demonstrates a dimension*location interaction between the different views. There was a main display effect for vertical performance ($F(2,72) = 33.1$ $p<.0001$), and a main display effect for horizontal performance ($F(2,72) = 43.17$ $p<.0001$). The close exocentric view led to worse vertical tracking than the mid or far views, (TMC 72 df, $p<.01$ per comp), while the far exocentric view led to worse horizontal tracking than either the near or mid views. (TMC 72 df, $p<.01$ per comp). This interaction suggests some form of performance tradeoff, whereby there was more accurate horizontal control at relatively closer viewpoints, and more accurate vertical control at the furthest viewpoint.

Situation Awareness (short term)

Average ERF scores showed a main effect of path and no significant effects of trial, or display type, while the average WRF score was influenced by map type and by path. Average response time for STM questions as influenced by map type and trial with no significant interactions. These results are examined in further detail below.

Display Effects: A Repeated measures analysis was performed on the average number of correct scores, with subjects nested within map type as shown in Figure 3.4. There was a significant main effect of display type, with average number of correct WRF questions differing significantly as a function of the type of display ($F(4,120) = 3.21$ $p<.02$). There was no main effect for ERF questions, and the only difference between display types can be attributed to the difference between the egocentric display (worst) and the mid-exocentric display (best) (TMC, 120 df P<.01 per comp).

There was also a significant effect of display type on response times ($F(4,120) = 4.51$ $p<.001$), as shown in Figure 3.5. The egocentric and the close-exocentric map types supported faster response times than did the planar display. (TMC 120 df, P<.01 per comp).

Further, each short term memory question was examined individually to determine any significant display main effects for the type of question asked. There were display main effects for three of the eight questions.

Question 1: Where is the runway in relation to your aircraft? (North, South, East, or West) The main display effect for this question was significant for both accuracy ($F(4,120) = 2.89$ $p<.03$) and for response time ($F(4,120) = 2.63$ $p<.04$). As seen in Figure 3.6, the far exocentric and planar views supported the most accurate performance for this question, while the egocentric view supported the least accurate performance (TMC 120 df, P<.01 per comp). Subjects' accuracy while using the mid exocentric and close exocentric displays did not differ. In terms of response time, individuals using the mid exocentric, and the planar displays took longer to answer the question than did individuals using the close exocentric display (TMC 120 df P<.01 per comp). Though there appears to be a speed-accuracy tradeoff contained within this question.

Question 2: In which general direction is the aircraft traveling? (North, South, East or West) Figure 3.7 plots both average accuracy and response time for each display type, both of which showed significant main effects for the type of display used ($F(4,120) = 4.26$ $p<.003$ and $F(4,120) = 3.84$ $p<.006$). The egocentric view led to least accurate performance on this question. Average performance by subjects using the other map types did not differ. (Tukey, 120df, $P<.01$ for each paired comparison). In addition, individuals using the planar display on average took longer to answer the question than individuals using the close exocentric view (TMC 120 df, $P<.01$ per comp.) Individuals using the mid, far, and egocentric views took about the same amount of time to answer the question.

Question 5: What is your aircraft's position relative to the flight path? (above & right, above & left, below & right, or below & left.) Figure 3.8 summarizes average accuracy and response times for each display condition. The main effect for accuracy was marginally significant ($F(4,120) = 2.16$ $p<.08$) while the main effect for response time was slightly more significant ($f(4,120) = 3.21$ $p<.015$). The close exocentric view led to more accurate responses than the far exocentric view, while no other comparisons were significant. (TMC 120 df, $P<.01$ per comp). In addition, participants using both the far and mid exocentric views took significantly longer than those using the egocentric view (TMC 120 df, $P<.01$ per comp).

No other questions showed significant differences in either accuracy or response time for the different map displays.

Path Effects: Four different paths were flown by each subject, and the average scores by path are shown in Figure 3.9. Accuracy by question was examined per path by using a repeated measures analysis on average scores for all eight questions. Average accuracy score on the STM questions was affected by path direction ($F(3, 140) = 6.7$ $p<.0003$), with northbound paths yielding significantly higher average scores than southbound paths (TMC 140 df, $P<.01$ per comp). There was no main path effect for average response times.

In addition, the two types of questions (ERF and WRF) were examined separately. ERF and WRF performance by the path flown are represented in Figure 3.10 There were path main effects for both ERF and WRF questions ($F(3,140) = 4.50$ $p<.005$) and ($F(3,140) = 4.04$

p<.009) respectively. However, the accuracy of responses seems to be roughly equivalent for both question types.

Trial effects Trial main effects were significant only for response times, such that the first trial took significantly longer than the other three trials to answer the questions (TMC, 70 df, P<.005 per comp.) This effect was sustained through all eight questions.

Situation Awareness (long term)

The map reconstruction task was evaluated by measuring and averaging the linear distance from each subject's placement of terrain features to the actual locations of the features within the world. A repeated measures analysis revealed that there were no main effects of display type on object placement. Neither overall placement error nor placement error for each individual terrain feature proved to be significantly different for the five display types. In addition, height judgment information was gathered but revealed no main display effects for overall performance nor for performance with individual terrain features. Qualitative viewing of the different questionnaires revealed that subjects very often had no idea where objects should be located and merely guessed, placing each object at some arbitrary location along one of the flight paths. In fact, certain subjects refused to complete the LTM task due to its difficulty and their speculation that they would merely guess at correct locations and relative heights. Thus, there proved to be a very large floor effect due to the fact that no subject got very close to perfect performance, and all subjects had placed at least one of the objects at a very great distance from where it should have been located.

Subjective Evaluations

Subjective evaluations were requested only after subjects had completed all four recorded trials. As Figure 3.11 indicates, overall average evaluations showed that subjects evaluated the close exocentric view as more difficult to use than any of the other exocentric views. (TMC, 35df, P<.01 per comp).

Further, each question requiring subjective evaluation of difficulty was examined separately for significant comparisons between displays (TMC, 35 df, P<.01 per comparison). These results are displayed together in Figure 3.12.

Question 5 :(difficulty answering SA questions such as "to the North or to the South".) The main display effect was significant at $F(4,35) = 4.13$, $p<.008$. Responses for the egocentric view indicated a higher difficulty than the responses for either the far exocentric view or the mid exocentric view.

Question 9: (difficulty making lateral judgments) The main display effect for this question was significant at $F(4,35) = 5.93$, $p<.0009$. Responses indicated a higher level of difficulty for the close exocentric view than for either the mid exocentric, the far exocentric or the egocentric views.

Question 10: (overall difficulty of the flying experience with the given map type) Significant display main effects were present ($F(4,35) = 4.7$, $p<.004$). The egocentric and close exocentric views were rated as more difficult than the planar or far exocentric views.

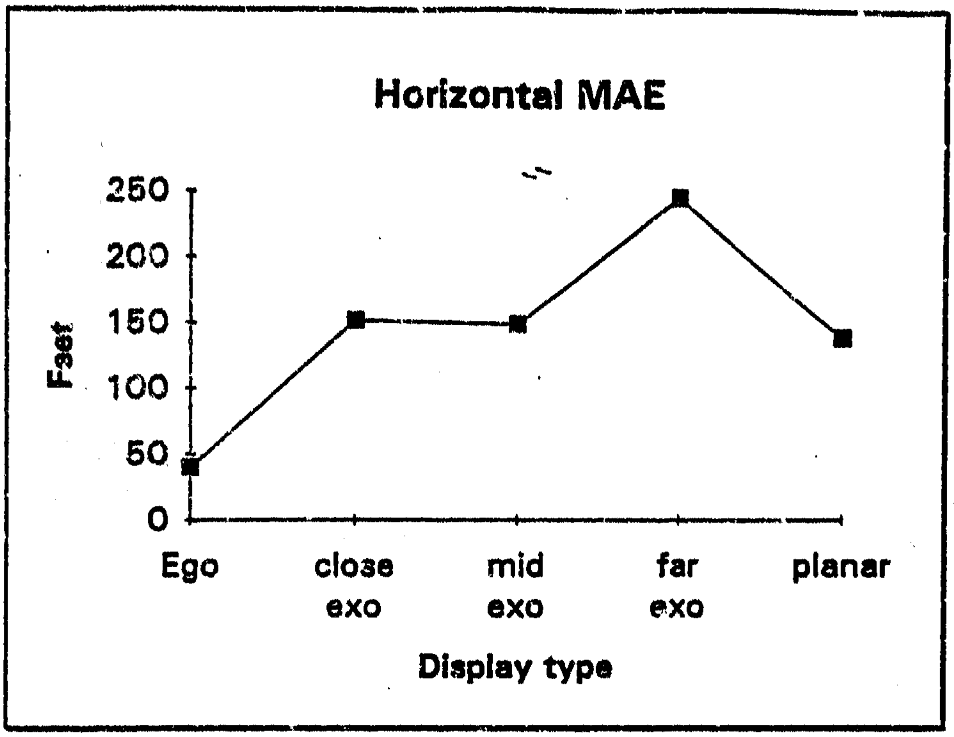


Figure 3.1: Horizontal error by type of display

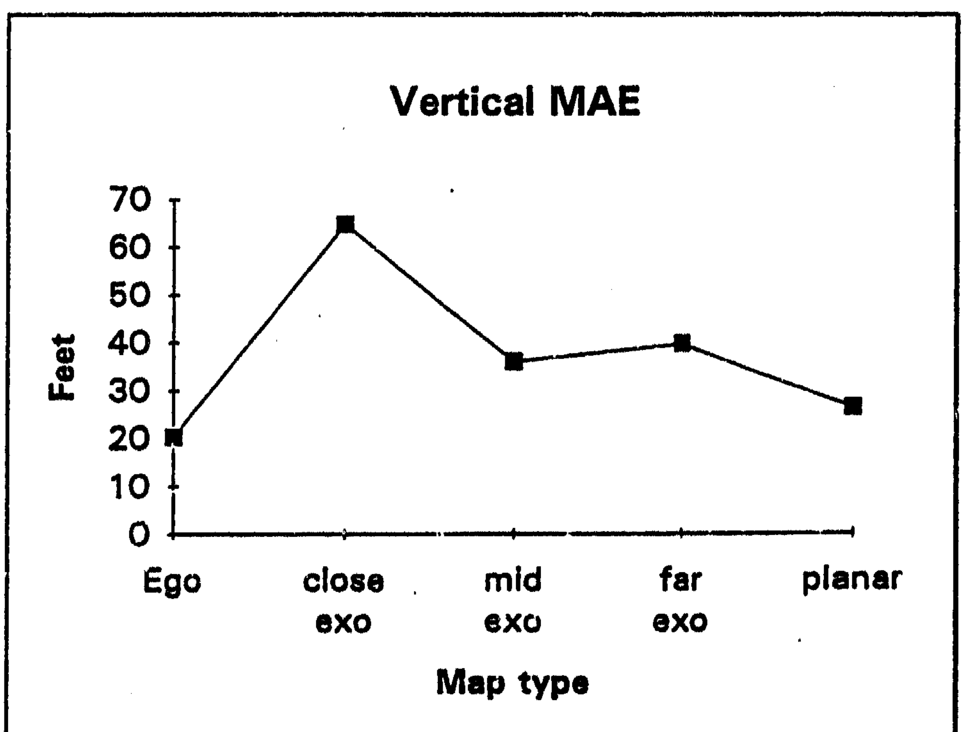


Figure 3.2: Vertical error by type of display

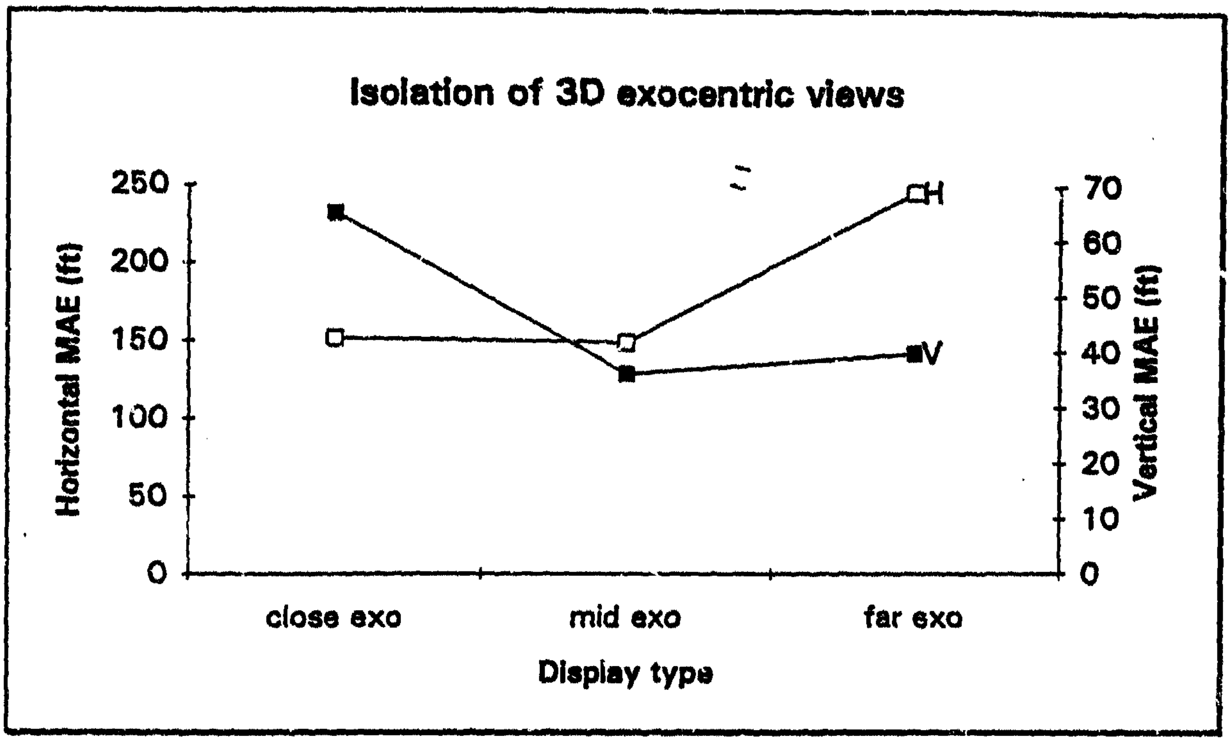


Figure 3.3: Isolation of exocentric 3D maps

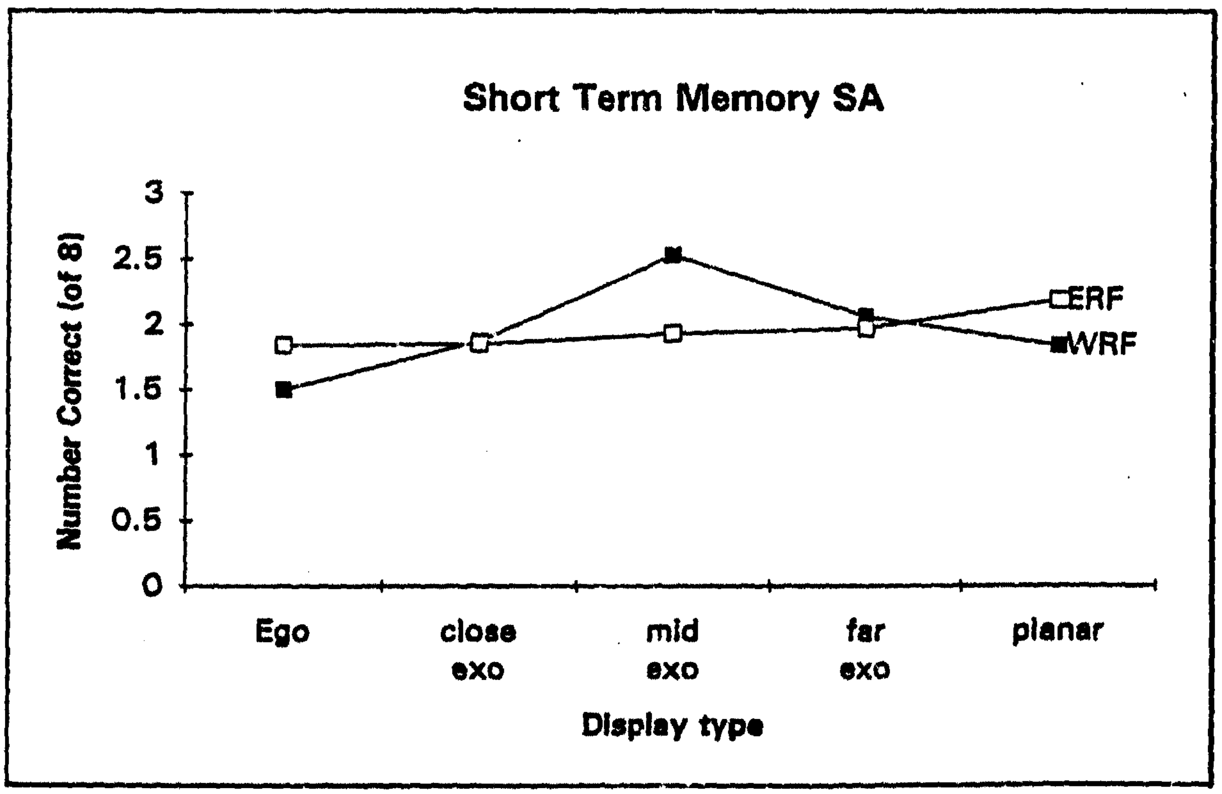


Figure 3.4: Average score on SA questions by map type

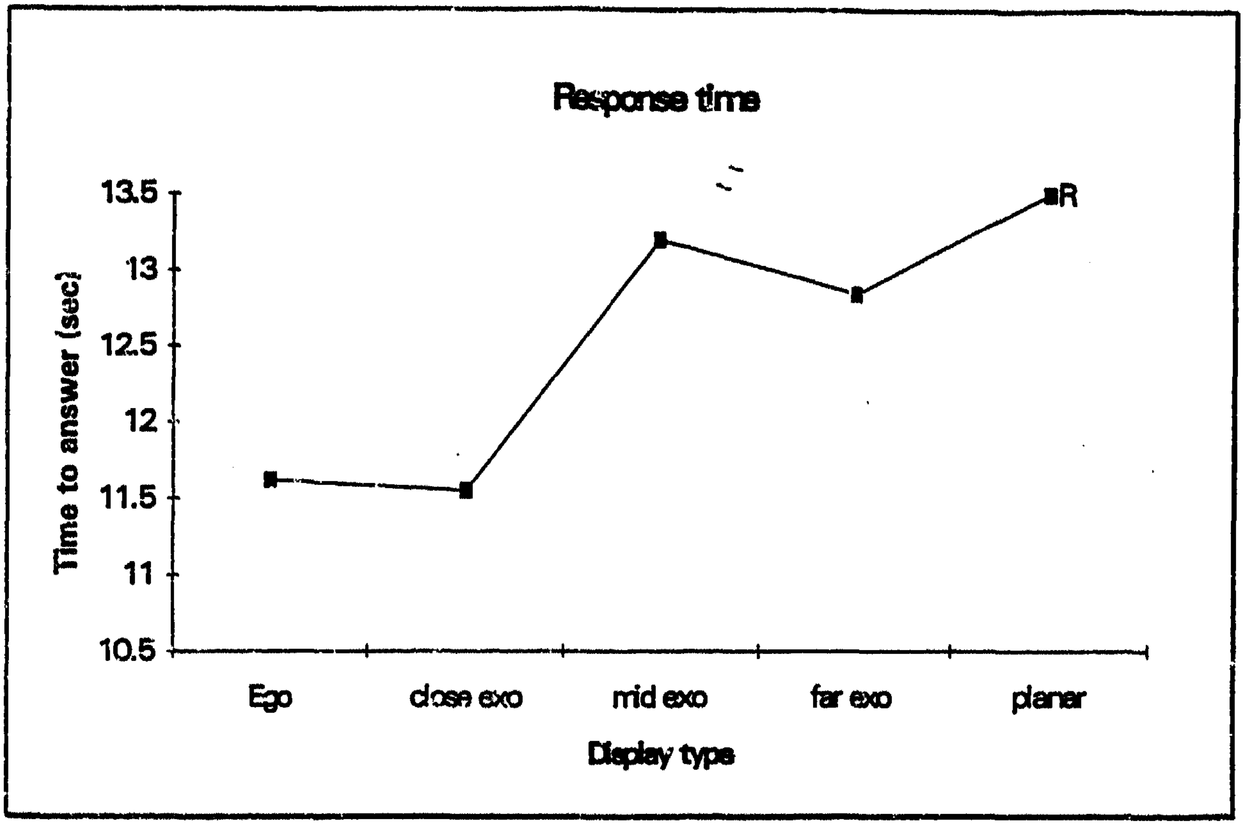


Figure 3.5: Overall STM performance by map type with response times

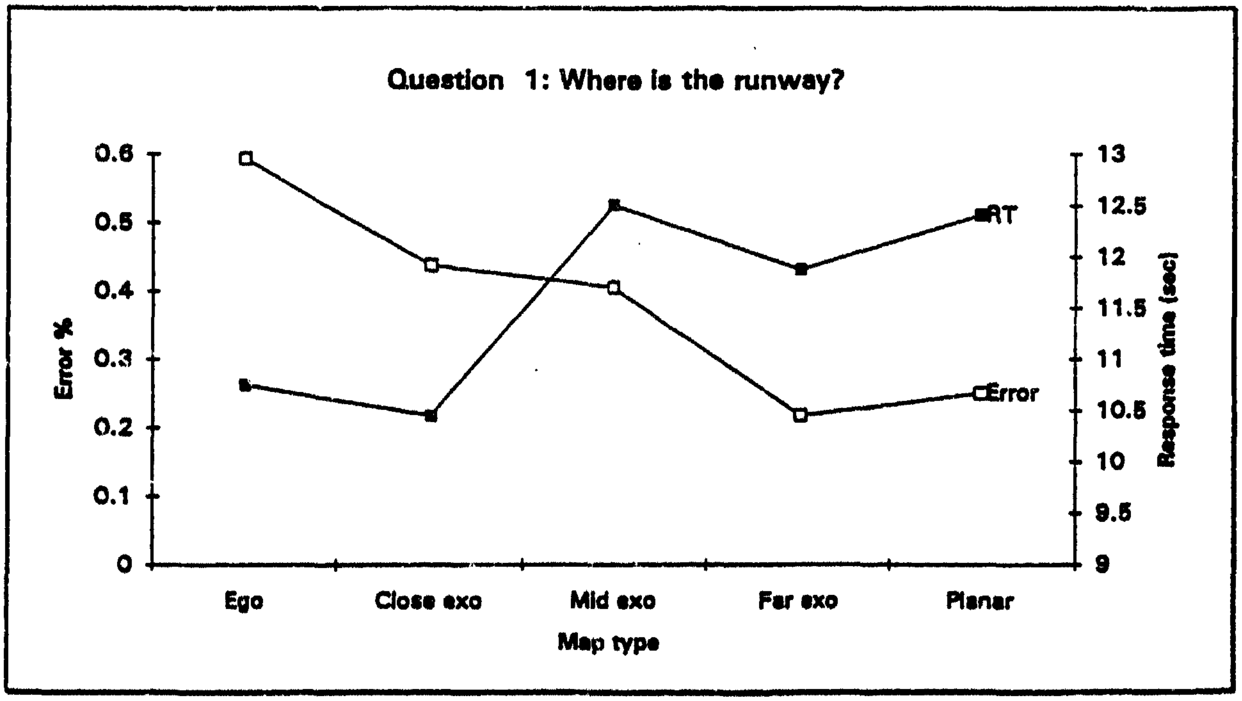


Figure 3.6: Summary of performance on question 1

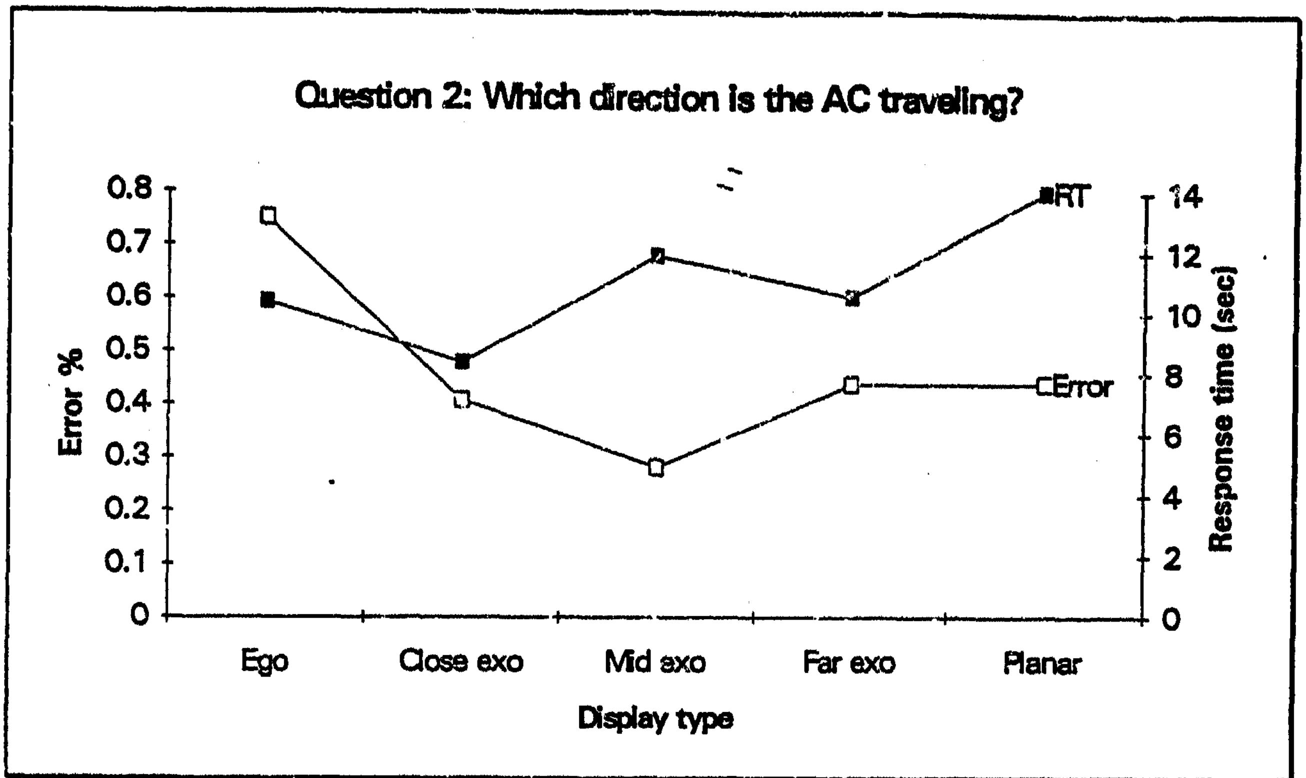


Figure 3.7: Summary of performance on question 2

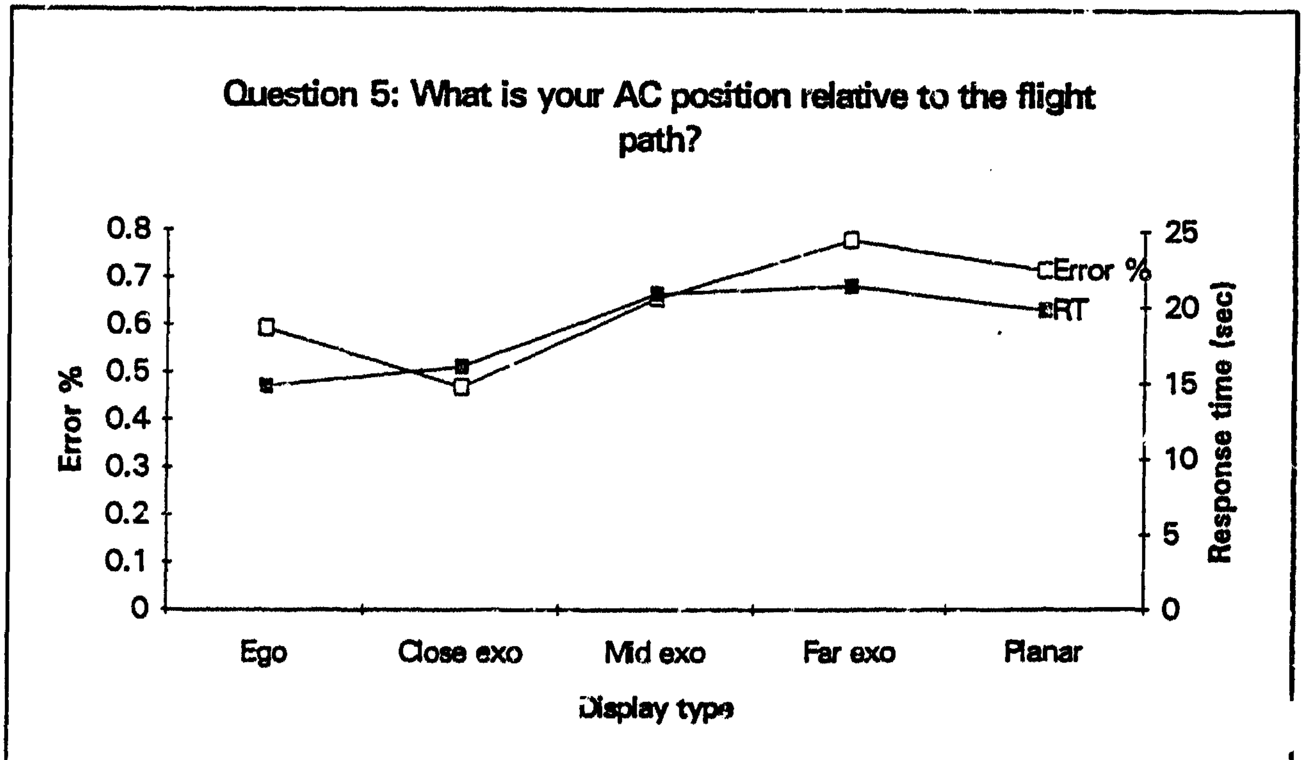


Figure 3.8: Summary of performance on question 5

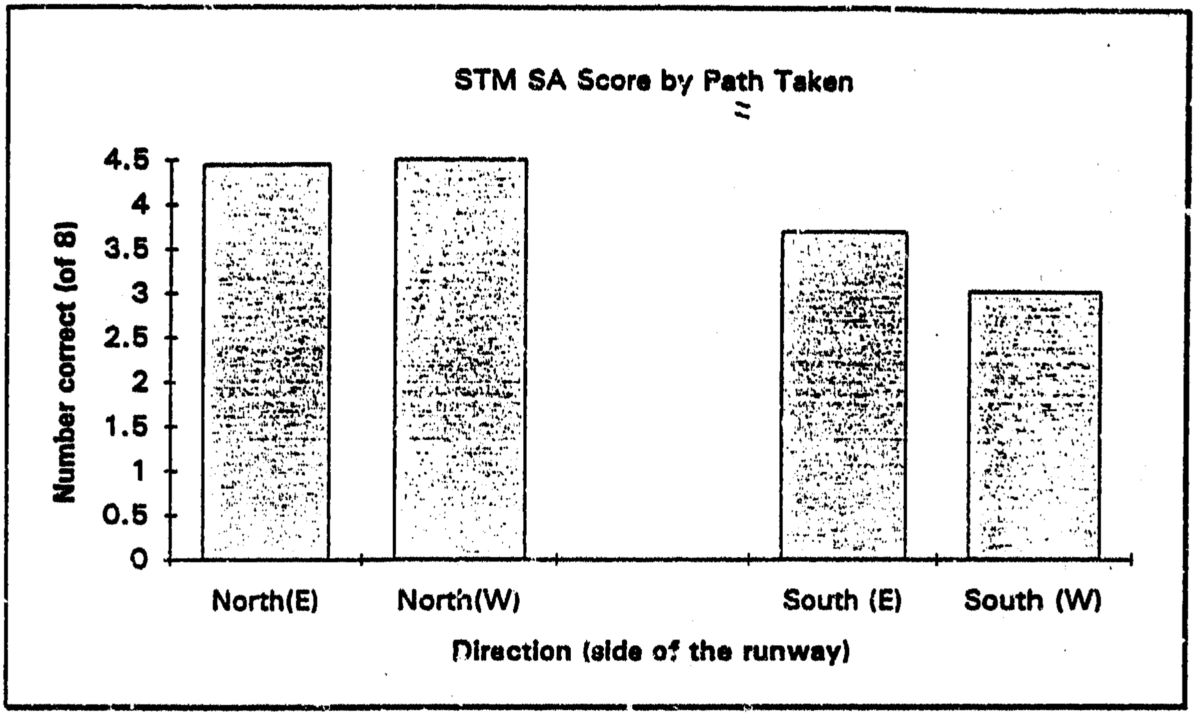


Figure 3.9: Average score by the path flown

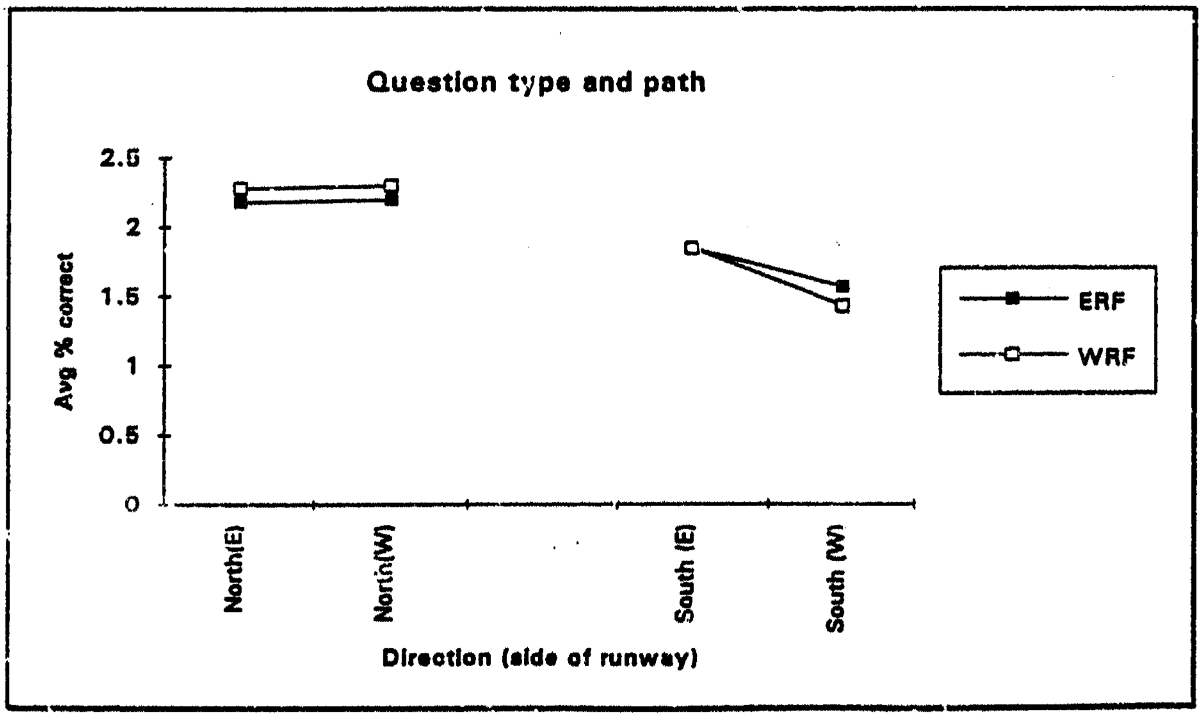


Figure 3.10: Summary of Performance on SA questions.

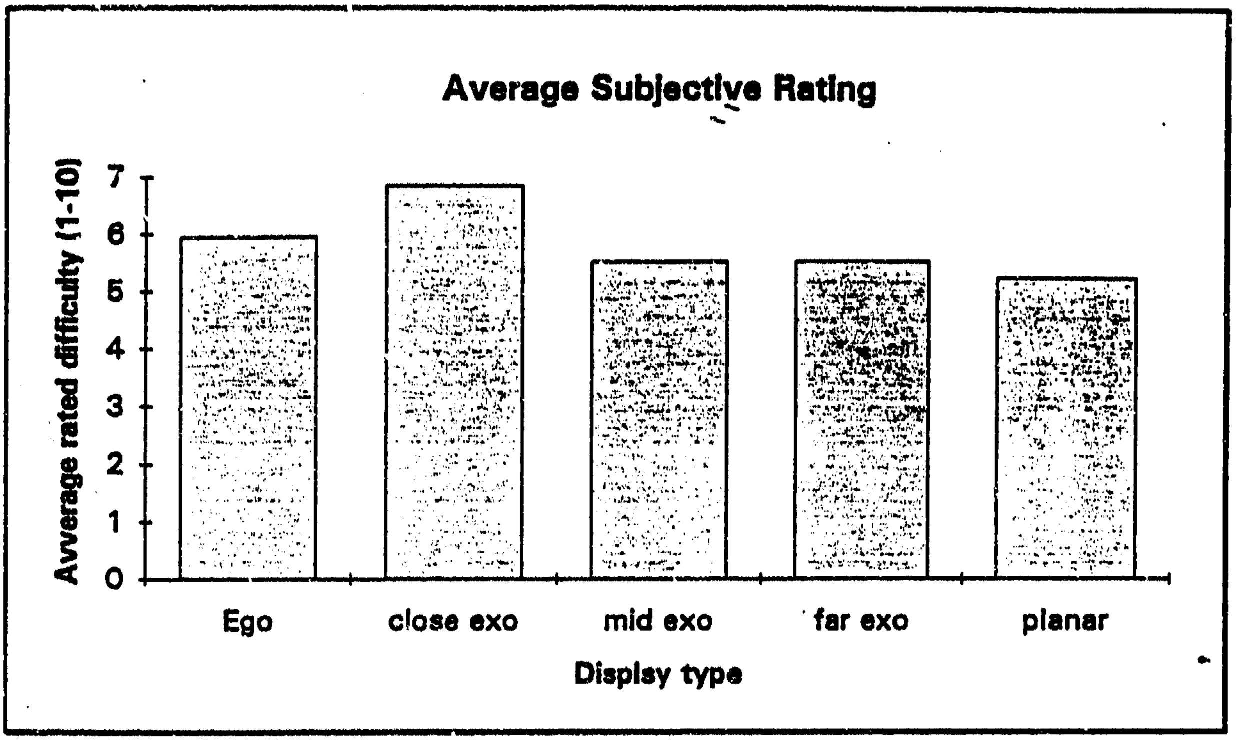


Figure 3.11: Average rating of difficulty for each map type

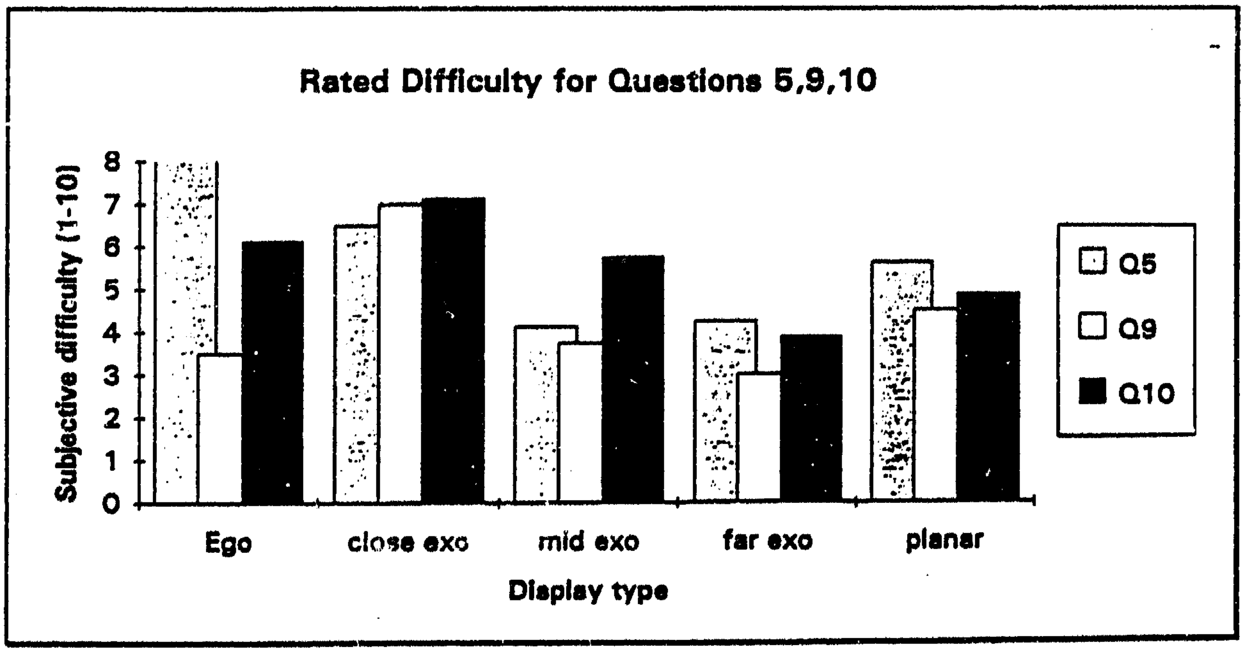


Figure 3.12: Summary of Subjective ratings for questions 5, 9,10

4. DISCUSSION

Tracking Effects

The egocentric display supported better tracking on both the lateral and vertical axes than the rest of the map types. The superiority of the egocentric viewpoint location to the planar instruments in terms of tracking error is consistent with Haskell & Wickens' (1993) findings and hence supports our hypotheses. In general, the 2D planar display supported better tracking performance than the 3D exocentric views, consistent with findings by Andre et al. (1991), as well as Rate & Wickens (1993) and Wickens et al. (1994). The tracking advantage for 2D displays over the exocentric perspective displays is presumably due to ambiguity of the confounded lateral and vertical dimensions in the latter displays. However, within these exocentric displays the mid-exocentric viewpoint distance seemed to be the best compromise between distance and distortion, providing the "best of both worlds", and actually supporting tracking performance that was as accurate on both axes as that provided by the 2D displays.. It is also important to note that these results were obtained even with cross-coupling of pitch and roll, such that the tracking task was truly integrated.

Most of the tracking performance differences between these displays were expected and understandable. However, a very interesting tradeoff within the 3D exocentric maps is apparent in Figure 3.3. This tradeoff indicates that the middle exocentric view supported better overall tracking performance than either the close view or the far view when both lateral and vertical tracking were considered -- a highly unexpected outcome. One would expect that as the viewpoint gets further (10-25-70K feet), tracking performance would gradually decrease due to decreased resolution of the display space in terms of graphic pixels, an effect documented by Kim et al. (1987). However, in the present study this decrease in resolution was partially offset by the fact that the GFOV was adjusted in order to keep the same amount of terrain visible for each of the exocentric perspective views. This effect can be quantified by combining the GFOV and the distance into one "compression factor". The ratio of the viewing distance can be specified as 10-25-70, and with direct viewing this would mean that the displayed visual angle subtending a given amount of true lateral error (in feet) would decrease by the Arctan function. For an arbitrary 10 unit true distance, the Arctan for 10/10,10/25, and 10/70 reveals angles of 45, 21, and 8.1 degrees respectively. When combined with the adjustments to the GFOVs (120, 80, and 45 deg.), display resolution can be identified by the ratio of the Arctan function to the GFOV (45/120 = .375; 21/80 = .262; and 8.1/45 = .18), with higher numbers indicating higher resolution. Presumably, better performance can be achieved when error resolution is high.

From these calculations, it is easy to understand the high lateral error at the far exocentric position, although why error is not increased at the medium distance relative to the near distance remains unclear. Correspondingly, it can be understood that, since vertical error is coded by color, as well as by spatial distances, it may very well be immune to the resolution factor. This color constancy across displays can account for the absence of vertical error differences between the mid and far exocentric positions, but does not explain the higher level of vertical error at the near position. Yeh & Silverstein (1992) found a somewhat similar tradeoff of tracking error type by viewing distance. They found that depth judgments were more accurate for a near distance, and that altitude judgments were more accurate for a far distance. We can only conclude that two different aspects of the display configuration are impeding tracking performance;

1. The first is resolution. At far distances the resolution of tracking deviations can be relatively small. Quite simply, it is harder to see a tracking error due to decreased resolution and therefore it is harder to correct that error.
2. Perhaps the extreme distortion caused by compressing a 120 degree GFOV into a viewing angle only around 60 degrees, is sufficiently disorienting to disrupt accurate vertical tracking at close distances, negating any advantages that may be present due to higher resolution.

Given the effects of these two aspects of display configuration, it can be proposed that the middle exocentric viewing condition gained the advantage of higher resolution, but was sufficiently close to the actual center of projection to avoid a performance decrease due to distortion.

Another sign of evidence for this unexpected tradeoff effect can be seen in subjects' evaluations of the difficulty of using the maps. Participants indicated that the close exocentric view was the most difficult to use, indicating that this view imposed a high level of workload and attention to the guidance task. Endsley (1993b) indicates that in some instances SA and workload may directly effect each other, and that the key is to identify situations which would lead to undesirable combinations such as high workload and low SA. In the present study it would seem that extremely close exocentric viewpoints with large fields of view create higher workload in display interpretation, while also creating a lower level of SA; clearly situations which should be avoided.

Situation Awareness

SA effects were also generally consistent with the hypotheses proposed in the introduction. . The highest average accuracy scores of short term SA were attained with exocentric viewpoint locations, particularly at the middle distance. The critical consideration here is that 3D perspective displays provided better performance than 2D planar displays with the same information. This outcome seems appropriate due to the ecological nature of 3D displays. Several studies (Ellis et al., 1987; Bemis et al., 1988; Wise et al., 1993) found similar advantages for exocentric perspective 3D displays. By the same token, it is important to note that the awareness advantage for 3D displays was limited to the exocentric viewpoint locations, and that awareness at the egocentric viewpoint location was poorer than awareness for subjects using the planar 2D displays.

Also, results found by Barfield et al. (1992) were replicated in that all of the god's eye perspectives outperformed the fully egocentric display in terms of response accuracy for short term situation awareness. Although, there was a slight response time advantage for the egocentric and near exocentric viewpoint locations as shown in Figure 3.5. Surprisingly, we found no selective advantage for the egocentric display on ERF questions. We might have predicted that due to the pilots eye view, ego referenced questions would be entirely consistent with the participants view, and this advantage would have been reflected in more accurate responses to the ERF questions. However, it is likely that we found no egocentric viewpoint advantage for ERF questions due to the fact that exocentric viewpoints were only exocentric in terms of viewpoint location, and that the viewpoint motion and orientation were linked to the aircraft motion such that even these displays were somewhat egocentric. Thus, rotating maps were created for all of the displays that allowed ERF questions to be answered without mental alignment of the display to the ERF.

The individual STM SA questions revealed some interesting trends as well. In question 1, Figure 3.6 demonstrates the classic speed accuracy tradeoff seen in so many different situations. For this reason, knowing where the runway is in relation to the aircraft seems not to be effected much by map type, even though there are significant differences in the average score of participants using different display types.

In contrast to the tradeoff seen in question 1, examination of questions 2 and 5 reveals a more clear interpretation. Responses to question 2 asking the momentary direction of aircraft flight (Figure 3.7) showed very little interaction of speed and accuracy. Subjects flying the egocentric view simply did not know which direction they were traveling, as their accuracy was around chance. A trade-off does appear to exist within the exocentric 3D displays, the mid exocentric viewpoint showing lower error rates, but higher response times. In addition, contrasting the far exocentric with the planar display did not reveal a change in error rate, but did show the highest response times with the planar display. In agreement with the overall SA performance, it would appear that performance on question 2 taking into account both speed and accuracy was best using the 3D exocentric displays. Question 5, assessing subjects' knowledge of their lateral and vertical location relative to the flight path, shows the greatest disparity between displays for the individual questions. There is almost no evidence of a speed accuracy tradeoff in this question, the egocentric and close exocentric view preserved subjects' knowledge better than did the mid exocentric, the far exocentric, and the planar displays.

One somewhat surprising finding was the absence of any effect of map dimensionality on questions 7 and 8. These two questions required that subjects judge the height of a near terrain feature relative to the aircraft. On the one hand, an advantage for the 3D display could have resulted due to increased integration of the visual scene. On the other hand, we might have predicted that the 2D displays would have supported more accurate performance than the 3D displays due to the fact that this judgment required focused attention to only the vertical axis. As predicted by Haskell & Wickens (1993) this focused attention task should be better supported by 2D displays which do not have the drawback of axis confusion. We can assume here that the advantage of the integrated 3D rendering may have been offset by this greater precision and reduced ambiguity while using the profile portion of the perspective display, and the end result was a canceling of the different advantages of each display type.

Path effects were found when Northbound paths were compared with Southbound paths. The reduced error when traveling north is consistent with the findings of Wickens et al. (1994) and many other studies (e.g. Aretz, 1991; Harwood & Wickens, 1991). The northbound advantage can be attributed to the need to mentally rotate the southbound paths in order to answer geographical questions. However, the northbound advantage was curiously evident in both WRF and ERF questions. The accuracy cost suffered by Southbound paths for WRF questions is very understandable and predictable, as the forward view is in a Southerly orientation, and responses require mental rotation to align the instantaneous heading with true North. However, ERF questions are dependent on only the instantaneous heading of the aircraft, and do not have to be translated to a World-reference frame. The reason an advantage for Northbound paths in terms of ERF questions remains puzzling. Two possible solutions may be offered:

1. It is possible that traveling North does not requirre constant resource dedication to maintaining awareness of the WRF, as subjects can directly perceive information. This leads to more processing resources available to keep alert of ERF information.
2. It could be that the questions were simply posed from locations along the Northbound paths which were easier to interpret. Examination of Figure 2.1 reveals that frozen screen locations for Northbound paths took place when headings were directly aligned with world coordinates (either North or West), while locations for the frozen screen task on southbound paths were at headings not consistent with world cardinal directions. It is recommended that further studies be accomplished with multiple locations for SA tasks to avoid possible confounds of this nature.

In addition to SA effects due to the map flown and the path taken, there was one significant main effect of trial; response times in the first trial were substantially longer than any other trials. This effect can be directly related to the fact that participants did not have any practice on SA questions, and the first trial was the first time they had been exposed to the questions. Since these questions were identical in each path, the fact that response time decreased with practice is hardly surprising. Subjects had two practice trials for tracking, which would explain why there was no parallel trial effect for tracking performance.

While the results for STM SA measures revealed many significant and meaningful effects, the lack of significant results for LTM SA was disappointing. Overall map recall scores were very poor, and there were no LTM differences due to display type at all, indicating no difference between the long term memory store of the terrain. The possibility exists that subjects simply did not have the duration of exposure to the experimental world and were focused too much on local guidance to encode many of the objects located within the domain; an effect which may also be apparent in actual flight missions. Also, all maps were rotating and hence would be predicted on the basis of Aretz's (1991) findings to fair poorly on this test because of the inconsistency of the location of landmark depiction across flights. The LTM recall task was presented specifically in terms of world referenced coordinates, and subjects had only observed landmarks through an ERF. Alternative methods of gaining information as to LTM store could involve decreasing the number of terrain features, or increasing exposure to the experimental domain. Either way, there is a need to evaluate the LTM SA imparted to pilots, and the present study failed to achieve a good measure of this construct.

Subjective Evaluations

The results of subjective evaluations indicate that participants using the egocentric and close exocentric displays felt those displays were difficult and demanding to use. This influence on perceived difficulty did not exactly match tracking performance, as tracking was actually best with the egocentric viewpoint location. Subjective ratings of difficulty were also in partial disagreement with STM SA response latency. While subjects indicated that the fully egocentric view and the close exocentric view were the most difficult to use, they responded more rapidly than did subjects using the other display types.

While this could be due to subjects simply guessing, we believe this is not the case, as subjects performance on the short term memory questions was above chance. Endsley (1993b) characterizes SA and workload as flip sides of the same coin, asserting that "Workload is generated directly from the effort it takes to achieve and maintain SA". While this statement appears to be somewhat true in this case, as the displays with the highest subjective workload had the quickest response times, it is not totally true, as subjects using the middle distance exocentric viewpoint had the greatest accuracy, but did not think the task was the most difficult. More research including the gathering of both subjective workload and awareness should be accomplished to further quantify the relationship between the two.

Overall Conclusions

First and foremost of our conclusions is that properly designed 3D displays can outperform 2D displays for navigation and for SA. However, this conclusion is dependent on the type of 3D display used; fully egocentric locations support better tracking performance, and exocentric locations support better SA performance. Also, not all 3D exocentric displays support higher SA. Only displays such as the mid exocentric distance are advantageous because they ovoid low resolution at far distances, and FOV distortions at close distances. Further examination of these 3D exocentric views in actual flying tasks is essential in order to define the exact location form which to display the map.

Within the four 3D display prototypes, Figure 4.1 depicts what appears to be a tradeoff between displays that support local guidance (the average distance from the flight path) and displays that support global situation awareness (the error rate on STM SA questions) when the viewpoint is moved from the most ego-referenced to a more exocentric reference frame. In Figure 4.1 the left-hand ordinate is tracking error as derived from average horizontal and vertical error, the right ordinate is scaled for average accuracy on short term awareness questions. Whether the fully egocentric display or the mid-exocentric display is "better" in this comparison depends upon whether one gives greater weighting to local guidance (egocentric) or global awareness (mid-exo). Given this tradeoff between global SA and Local Guidance revealed as the degree of egocentrism in the display increases, it would seem that the ideal use of electronic aviation displays for guidance to landing should incorporate a 3D exocentric view for higher levels of the flight path where exact guidance is not quite so important, but that for approaches close to the ground, where guidance is extremely important, a 3D egocentric display proves to best support accurate guidance.

An important limitation to the generalizability of the results of present study, is that performance was assessed while only using an electronic display, and not in an actual flying environment, and hence characterizing instrument meteorological conditions. The displays could interact very differently if used in conjunction with other flight instruments, or with an actual forward field of view as in visual contact conditions, where ERF to WRF transitions are required to maintain controlled flight. Nevertheless, given discussions in further development of zero visibility landing displays for pilots, the current evaluation has a great dial of potential relevance.

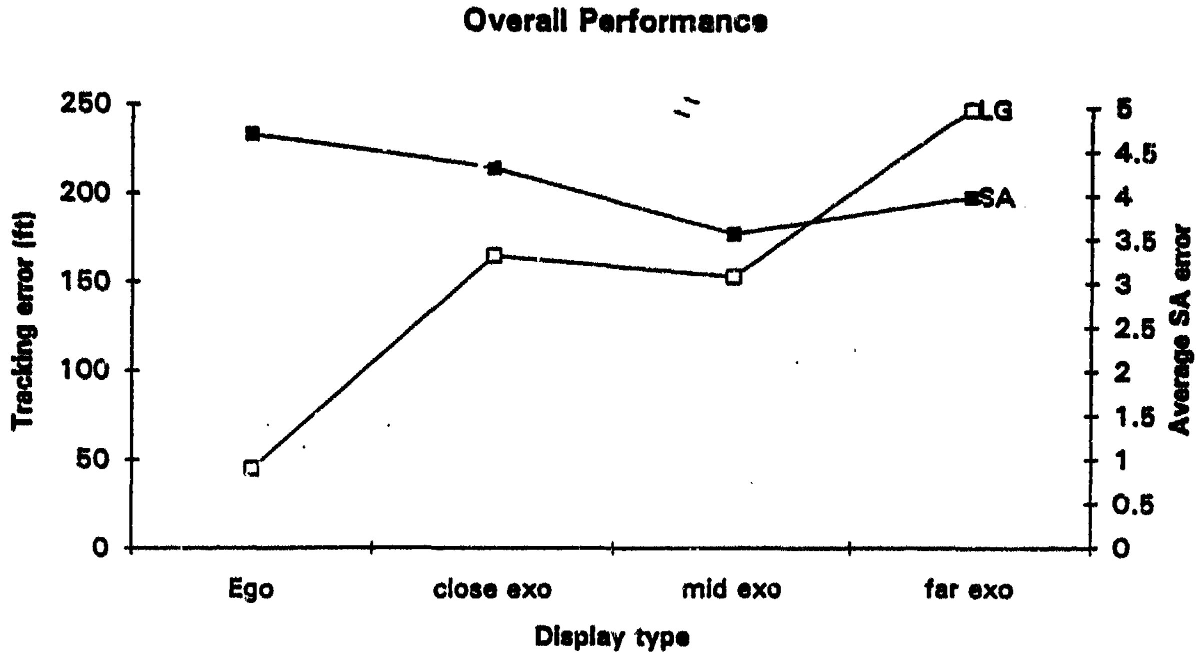


Figure 4.1: Summary of performance, both in terms of SA and LG Tradeoff is apparent in the interaction of LG and SA. Data is for overall score on STM SA tasks and tracking error as defined by average horizontal and vertical MAE.

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Appendix A

PLEASE READ THESE INSTRUCTIONS CAREFULLY

The Reason

The conventional paper approach plates are cluttered, and have been occasional sources of geographical disorientation and high cockpit workload. In addition, such paper plates are difficult and expensive to update or change in accordance with a new flight path in the terminal area. Electronic displays in the cockpit bring the potential to substantially redesign the approach plate format, and our research, supported by NASA, is intended to support this redesign effort. The purpose of this experiment is to evaluate different types of electronic maps, some of which depart considerably from the conventional type of paper approach plate.

You are to fly a total of six approaches. The first two will be practice runs, and the last four will be recorded. You will fly each of four different approaches to the same runway, in the same simulated airport area.

The Displays

You will fly one of five different display types:

1) sitting in the pilots seat, looking out the windscreen (figure 2.2)
2) outside viewing of the aircraft from a near distance (figure 2.3)
3) outside viewing of the aircraft from a medium distance (figure 2.4)
4) outside viewing of the aircraft from a far distance (figure 2.5)
5) viewing the aircraft in a planar or bird's eye view.(figure 2.6)

The task is the same for the different display types, however, the visual representations are what changes. Also, the same amount of the simulated terminal area will be displayed regardless of which type of map you use.

Your Task

You will see a flight path and obstacles. Your job is two-fold. First, keep the aircraft as close to the flight path as you can, and second, remain aware of the geographic and dynamic situations. (i.e. know where you are on the flight path, and where important terrain features are around you.)

To Help You

There are several items added to the display to help you fly. 1)There is "flight box" around the flight path, which shows you an alley down which you are supposed to fly. 2)The aircraft changes color if you are too high or too low: red for very low, yellow for a little low, black if you are acceptably close to the flight path, gray if you are a little too high, and white if you are very high. 3)There is a predictor present which shows you where the aircraft's nose is pointed. 4)Cardinal directions (N,S,E,W) are displayed on the terrain with appropriate white arrows showing the respective direction. 5)Finally, there is an ADI available for your use, it is set up with a moving aircraft and a fixed horizon.

How You Will be Assessed

The computer will record your deviations from the flight path, both vertically and laterally. In addition, at any time during each flight, the simulation will stop and you will be prompted to answer eight multiple choice questions designed to test your knowledge of the terrain and your current situation. On these questions, respond appropriately 1,2,3 or 4; both your response time, and your accuracy will be recorded. After completion of all your approaches, you will be asked to reconstruct the terrain that you flew through.

NOTE:

Due to the fact that all displays show the same amount of the terrain at different locations, some of them are subject to distortions which you might not be familiar with. The Dynamic flight environment of the simulation DOES NOT necessarily represent what you would actually see if you had a windscreen to look out. The distortion is somewhat like the effect of looking out a front door peep hole, where you can see quite a bit of the hallway, but it looks very distorted (although not quite as drastic). In terms of the computer screen, if you point to objects on the computer screen, that will not necessarily correlate with where you would point to the object if you were looking out of a windscreen.